Dance with the time: Emergent Quantum Mechanic and Time's arrow

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Introduction

What is wrong with the foundations of physic? Despite a lot of efforts, we don't have a satisfactory answer to the origin of the time's arrow and to the interpretation of the quantum theory. The usual approach is based on split/dual worlds where the physical laws are different in each domain: quantum theory applies to particle physic while the macroscopic objects follow the classical laws. Similarly, physical laws are reversible for a single or a small number of particles while they are irreversible when their number becomes large. Our approach is radically different by rejecting this duality and by claiming the physical laws must be valid at the fundamental level; the arrow of time must exist or emerge for a single particle and the classical world must emerge from the quantum laws but for decades, both these issues have been tackled unsuccessfully.

Our claims are based on a simple principle, "emergence from nothing" to derive the quantum laws and to elaborate the notion of time. If the Universe is emerging from nothing, not only the stuff (matter, particles,) but also the physical laws ("Law without law") and the space-time must emerge from nothing. The minimal assumption is to consider a quantum vacuum with some random fluctuations without space and time. The laws of physic are emerging from the random walk of the particle.

The 1st part of the document is dedicated to the emergent Quantum Mechanic (e-QM) which solves all the weird issues of the QM like the explanation of wave/particle dualism, the origin of the probability amplitude or the problem of measurement and wave collapse.

In the 2nd part, we address the reversible/irreversible issue which is related to the entropy increase at the fundamental level. The arrow of time emerges naturally from e-QM. A more speculative view of the number of space-time dimensions is touched at the end of the paper.

Emergent Quantum Mechanic

Standard Quantum Mechanic (QM) explains mathematically but not physically the wave and particle dualism which is blindingly obvious in the double slit experiment (Fig.1).

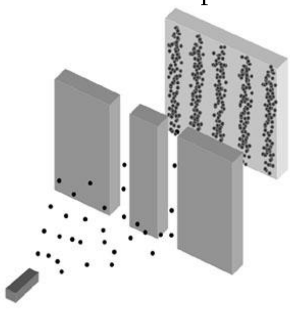

Figure 1: Double slit experiment showing the wave/particle dualism

The particle emitted from the source has an extended (non local) and deterministic behavior and at the same time, is measured probabilistically at a single location on the screen. The deterministic extended behavior is described by the Schrodinger equation while the probabilistic and local appearance is described by the measurement process (wave function collapse given by the $\psi^*\psi$ probability). This non-local and probabilistic behavior deserves an explanation especially in a local and deterministic classical world.

As emphasized in the introduction, the physical laws must emerge from nothing and using very simple assumptions, QM is emerging naturally without the usual difficulties for explaining the probability amplitude and the wave collapse during the measurement process. In the following, the QM description is largely based on the Feynman Path Integral formalism [ref 1] which is the closest to a physical interpretation. The principles of QM path integral are (Fig.2):

1. **Many paths**: a "particle" follows many paths in parallel.
2. **Contribution from one path "a" to "b" :** exp(iS(b,a)/ħ) where S(b,a) is the classical action along the path from a to b.
3. **Adding the contributions**: at each space-time point, the contributions from each path must be added. The sum of the contributions is usually called the Kernel from a to b: $K(b,a) = \sum_{paths} e^{+iS(b,a)/\hbar}$
4. **Moving forward and backward in time along a path**. Note: in the non relativistic case, only the forward in time paths are allowed.
5. **Must be supplemented with the usual add-ons in QM:** where Ψ(b) = ∫ K(b,a) Ψ(a) da is the wave function
   - **Probability of finding the particle at b:** $\Psi^*(b)\Psi(b)$
   - Ψ **collapse:** when a particle is measured/observed at b, Ψ is replaced instantaneously by a Dirac function δ(b)

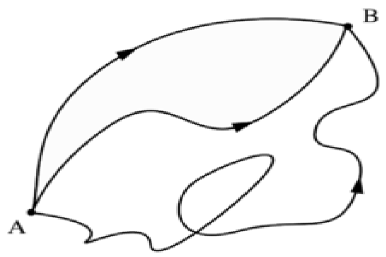

Figure 2: Parallel trajectories followed by a particle from A to B

In QM, the main contribution to the kernel K(b,a) is given by the paths close to $S_{cl.}$ and the major contributions are coming from the paths around S_{cl}.

Principles of e-QM

As mentioned before, the physical laws must emerge from nothing and several assumptions are coming from this principle. Eventually, all of them must emerge from nothing.

1. **Local** behaviour: no non-local interaction. With a space emerging from nothing, it does not make sense to have interactions through space.
2. **One single path**: the particle is always located at one place along a single path. It's the key point to observe a particle in one single location during the measurement process. This principle is coming from the "local" assumption (see above). The classical appearance is due to this single path assumption.
3. **Moving forward and backward in time**: particle paths are un-oriented and there are no specific direction for space and time. The particle's path is making many loops in space-time.
4. **Interaction with the vacuum**: The vacuum is modified by the particle interactions. A particle adds its contribution to the memorised contribution. This principle is important to recover the QM.
5. **Contribution from a path:** exp(iS(b,a)/ħ) where S(b,a) is the classical action. This is similar to the Feynman path integral approach. This assumption is not coming from the "emergence from nothing" principle but by considering the time as a rotation in another spatial dimension.

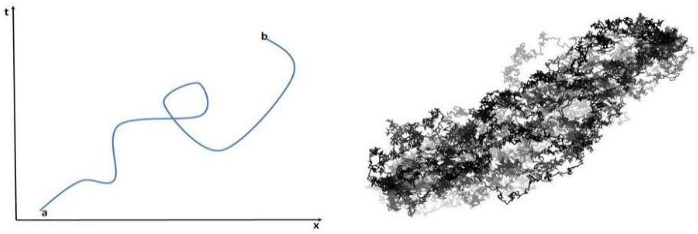

Figure 3: single path in e-QM: it could be simple (left) or very intricate (right)

These principles are physically sensible contrary to the standard QM principles which introduce the non locality in the parallel paths followed by the particle. In e-QM, the particle is always in one location. Locality is inherent to e-QM but we have to explain how the quantum behaviour (non deterministic) is emerging. In Fig. 4, a particle follows a path from a to b but since it goes forward and backward in time, it could passes at many different x values at the same time t (see Fig. 5).

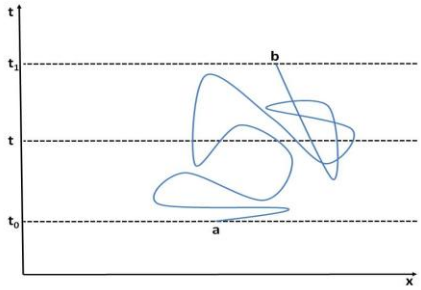

Figure 4: a single path followed by a particle from a to b

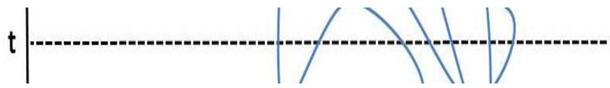

Figure 5: zoom at time t (from Fig.4), the particle could be located at several places

Where is the particle at time t? There are several locations for each time value and a probability is associated with each position. The non-locality for a specific time value emerges from the trajectory moving forward and backward in time. Note: the function is complex and the probability p(x) is not simply given by f(x)/Σ f(x).

Emergence of QM

At each intersection of the path with itself, the contribution G(b,a) in e-QM is not given by one path but by a sum over paths. K(b,a) and G(b,a) being respectively the contributions of a particle from a to b in QM and e-QM, we show the equivalence of G and K for simple paths which could be easily extended to more complicated paths.

Using the principle that a path adds its contribution to the previous path at the intersection point, the contribution of one single path is equal to the sum of many parallel paths as can be shown graphically for a single loop in Fig.6. In Fig.6a, a particle start in a and get a contribution $G_0(b,a) = \exp(iS(b,a)/\hbar$ in b by following the path from a to b. In Fig. 6b, the particle makes a loop and comes back to b adding its new contribution to the previous one: $G_1(b,a) = G_0(b,a) + \exp(iS_1)/\hbar \times G_0(b,a)$. The particle then goes to c (Fig. 6c) giving the contribution $G(c,a) = G_1(b,a) \exp(iS_2)/\hbar$. Expanding $G_1(b,a)$, we get $G(c,a) = \exp(iS_2)/\hbar \times [G_0(b,a) + \exp(iS_1)/\hbar \times G_0(b,a)]$ which is identical to the contribution of two parallel paths from a to c as shown in Fig. 7a and b.

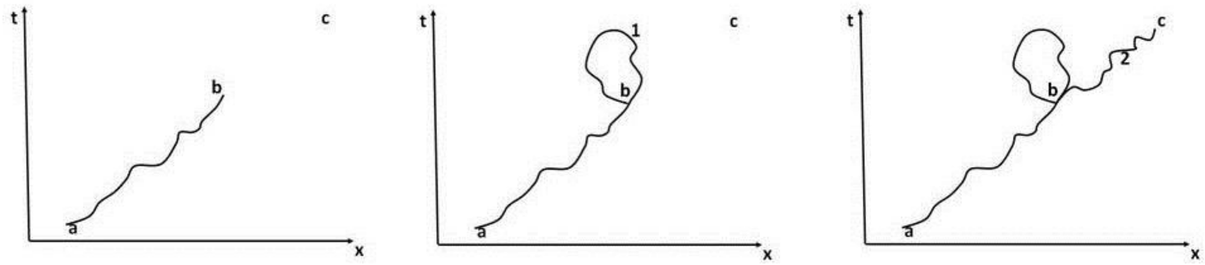

Figure 6 : a) the particle starts in a and goes to b. b) It returns to the point b by following the path 1. c) It goes again to c by following the path 2

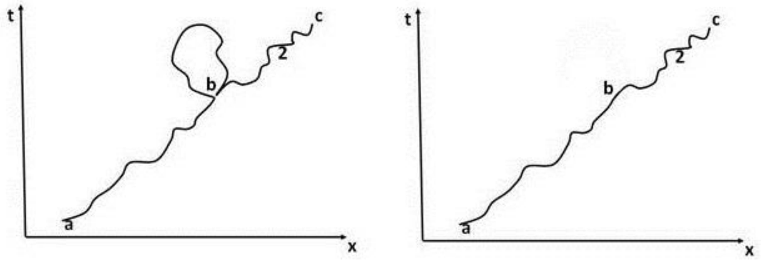

Figure 7 : a) the path from a to c makes a small deviation around b. b) the direct path from a to c. Both of them contributes to G(c,a).

For a single loop, we get the contribution of two parallel paths. The number of parallel paths is given by $2^{\text{number of loops}}$. In the standard QM, the particle follows a fractal trajectory of Hausdorff dimension 2 [ref. 2,3] meaning it covers a 2-dimension surface. The path will be very complicated with many crossing points and then the number of parallel paths will be huge. This is not an mathematical demonstration but we can easily infer the G(b,a) contribution is the sum of many parallel paths from a to b which is identical to the Kernel K(b,a) from the Feynman path integral in QM.
The total contribution G**(c,a)** is then **Σ parallel paths** which is the kernel **K(c,a)** in standard QM.

Wave function:

$G(x,t;x_i,t_i)$ gives the contribution for a particle starting from (x_i,t_i) and moving to (x,t) but the total contribution must be summed over all starting points. Assuming an initial distribution $f(x_i,t_i)$, the total contribution will be given by:

$$\Psi(x,t) = \int G(x,t;x_i,t_i)\ f(x_i,t_i)\ dx_i\, dt_i$$

Ψ(x,t) is the distribution x at time t and we recognise the standard the wave function in QM. The Schrödinger equation for Ψ is derived from $G(c,a) = \Sigma_b\ G(c,b)\ G(b,a)$ following the usual QM derivation [ref. 1, 4].

Probability amplitude

For a particle located at the space-time point a, G(a,a) = 1 which could be written as:

- $G(a,a) = 1 \Rightarrow \Sigma_b\ G(a,b)G(b,a) = 1$

Using G(a,b) = G*(b,a), we get

- $\Sigma_b\ G^*(b,a)G(b,a) = 1$

G*G being a real positive number and summing up to 1 is a probability. When we integrate over an initial distribution, G becomes Ψ and **Ψ*** Ψ(x,t) becomes the **probability** to find the particle at x and time t. It is important to point out the particle is always located in one place at a given time so there is **neither a measurement problem nor a wave collapse.** At a given time t, the particle could be located at several x values (Fig. 5). Due to the probability, e-QM is a non deterministic theory.

Notice: after the detection/measurement of a particle, we can neither predict the future nor retrodict the past location with certainties. Only a probability could be defined.

Quantum entanglement

QM shows non local properties which are particularly manifest in the entanglement and in the EPR experiments. The entanglement in QM shows an instantaneous correlation between two "remote" particles. The Bell's theorem seems to rule out any realistic and local explanation. e-QM being a local theory, this contradiction with the Bell's theorem must be explained.

The entanglement appears when two particles are emitted from a common location and they are sharing a common property. It is usual to consider two particles emitted with opposite spins ↑↓. At time t_0, the pair is entangled with spins up and down (↑↓) then each particle moves separately up to time t_1 where a particle is measured in ↑ state. The other particle is simultaneously measured in ↓ state as in Fig. 8.

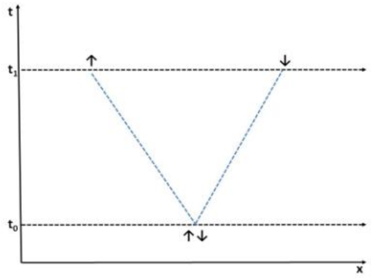

Figure 8: the pair of particles is emitted with opposite spins. At time t_1, they are measured simultaneously with a perfect correlation

The perfect correlation is natural for two classical particles without any **non local interactions** and no magic law; the space correlation is coming from a correlation in past time.

But real particles are following the quantum laws; the pair is entangled in state ↑↓ at time t_0. The pair then moves between t_0 and t_1 but nothing can be said about their correlation (spin orientation) before the measurement! At time $t_{1,}$ one particle is measured in ↖ state. This state is one of the possible states (Non deterministic theory). The other particle is simultaneously measured in ↘ state. There is a perfect correlation; QM shows an **instantaneous non local** interaction (Fig.9). There is no way to infer the state at time t_1 - ε. QM and experiment show an interaction speed faster than c. This instantaneous non local interaction is in contradiction with the special relativity and is a major mystery of QM. One possible explanation involves an interaction moving backward in time (up to the initial point) and then moving forward in time (up to the 2nd particle) but this interaction is also weird.

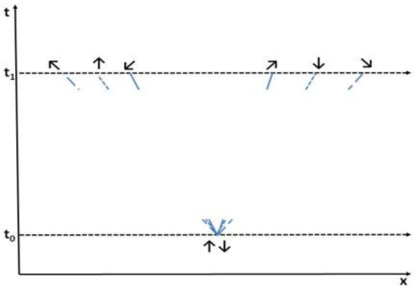

Figure 9: At time t_1, the particles are measured simultaneously with a perfect correlation but the orientations are given by quantum probabilities, not by the initial orientation.

The e-QM is a local and non-deterministic theory but is able to explain the non local entanglement by the particles moving forward and backward in time. By moving backward, the pair will interact several times and change their orientations but keeping them opposite (Fig.10):

- At time t_0, the pair is emitted with the spins ↑↓. The separated particles could go up to t_1. Moving backward in time, they could interact and change to ↖↘.
- At time t_1, the pairs could be ↑↓ or ↖↘ or ↙↗.
- If a particle is detected in ↖ state, the other will be in ↘ state.
- The detection of a pair in ↑↓ state at t_1 does not mean it was in the same state at time t_1 - ε.

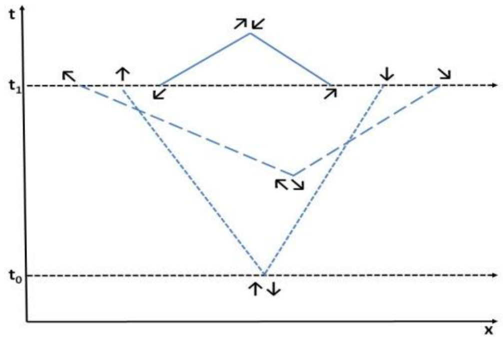

Figure 10: At time t_1, the spin orientations of the pair could come from different time (past or future) location and we could only give a probability but the spins will always be opposite.

Summarizing the explanation of entanglement by e-QM:

- Due to the forward and backward in time paths, there are many local interactions between the pair at various time t_i
- After a local interaction, the spin orientations of the pair of particle could change but keeping it opposite.
- At measurement time t_1, the spin orientation of each particle depends on the last local interaction. Their spin orientations are given by a probabilistic distribution but with an opposite orientation.
- Once measured at t_1, one cannot retrodict the spin orientation at $t_1 - \varepsilon$. Its value is only probabilistic.

Bell's theorem

The Bell's theorem is also related to the non local behavior of QM and is a major challenge for any attempts of a local theory. Actually, J.S. Bell deduces his inequalities based on two assumptions which must be satisfied by any realistic theory [ref. 5, 6]:

- **Locality**: the properties and the interactions are local so two entangled particles $|1,2>$ will evolve to two independent states $|1> + |2>$
- **Determinism**: the theory is deterministic (for a given input, we have the same output) and depends on a hidden variable λ.
  - Depends on a shared value λ (set initially): $|1, \lambda> + |2, \lambda>$
  - This variable is hidden, so it must be integrated: $\int d\lambda\, \rho(\lambda)\, \{|1, \lambda> + |2, \lambda>\}$ with $\int d\lambda\, \rho(\lambda) = 1$

The Bell's inequalities deduced from these assumptions are not satisfied by QM and the experimental results confirm the QM. Determinism entails each individual state has a determinate value prior to measurement. e-QM is a local but non deterministic theory so the 2nd assumption does not apply so e-QM is not rule out by the Bell's theorem.

Decoherence

Decoherence suppress the quantum properties, the particle becoming a classical object (locality and determinism). In QM, this quantum to classical transition happens either during the measurement process or during the interactions with the environment. A lot of studies have been devoted to decoherence especially the one due to the environment [ref. 7 and references therein]. The formalism uses the density matrix ρ. During the interactions with the environment, the ρ matrix is diagonalized but this mechanism is not sufficient to explain the quantum to classical transition in QM. To fit the classical world, the ρ matrix must be reduced to a single state; one way is to supplement QM with the many worlds [ref. 8] concept (Fig. 11). Decoherence in QM is always associated with a loss of information and entropy increase.

$$\rho = \begin{pmatrix} a & h & k & . \\ e & b & i & . \\ . & f & c & j \\ . & . & g & d \end{pmatrix} => environment => \begin{pmatrix} a & 0 & 0 & 0 \\ 0 & b & 0 & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & d \end{pmatrix} => Many-worlds => \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & x & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Figure 11: Transition from quantum to classical in QM

In e-QM, the particle is always localized so there is no need to look for an additional mechanism to explain the quantum to classical transition. Nevertheless, other particles interact with the quantum vacuum and blurs the phase of the particle (the phase $\Sigma\ e^{iS(b,a)/\hbar}$ => 1). This loss of information or decoherence in e-QM increases the entropy S. It must be emphasized the decoherence mechanism in e-QM involves either the interaction with another real particle or the loss of phase contribution due to the others particles blurring the quantum vacuum. In the next section, we address the relation between the entropy increase and the arrow of time.

Arrow of time and irreversibility

There are many arrows of time [ref. 9] like the thermodynamic arrow (mixing coffee and milk), the biological arrow (remembering the past but not the future), the cosmological arrow (expansion from the big bang) or the quantum arrow (measurement process) by naming a few. They are related and the consensus is to consider the cosmological arrow of time as the origin of all the others. Since the physical laws are reversible, the only way to create a time direction is by starting the universe with very improbable initial conditions. This setting at initial time looks like a circular demonstration: the arrow of time is defined by an arrow of time [ref. 10]. It is also unsatisfactory to explain the mixing of coffee and milk in my cup by the low entropy value 13 billion year ago. As noticed in the introduction section, in our opinion the irreversibility and the time's arrow must emerge at the fundamental (microscopic) level. We start by defining the criteria required to generate an arrow of time at the fundamental level and then they are applied to classical and quantum physics and finally to e-QM.

Mechanisms for generating a time's arrow

Two basic mechanisms are required to generate a time's arrow for a particle

1. A mechanism **introducing the changes**: it is an obvious requirement for time to exist. Changes are reversible. Quantum fluctuations and Brownian motion fit well this mechanism.
2. A **loss of information** mechanism: the irreversibility is coming from the loss of information. The mechanism must select one among many states. This selection mechanism could be defined by two supplementary criteria:
    a. an **evolution to many states**: a non-deterministic law of the type "1 to N states". This evolution is reversible.
    b. a **mechanism selecting one state**: the irreversibility is associated with this law. There is a loss of information (increase of entropy).

Applying these criteria to classical mechanic and QM

Classical mechanic

Classical mechanic (CM) is fundamentally determinist and the criteria 2a and b do not apply. It has no built-in concept of probability. For many particles, statistical mechanic is used to generate an arrow of time in CM. It refers to macro-states containing many equiprobable µ-states. There is no place for objective probabilities at the µ-state level. Probabilities are emerging from coarse graining where indiscernability is essential to the theory [ref 11]. Probabilities could only enter as a human ignorance so entropy in CM is an anthropocentric concept. So CM is not able to generate an arrow of time for a single particle and is even questionable for many particles. Since we are looking for an arrow of time for a single particle, we can conclude than CM is not able to generate a time's arrow.

Note: The **chaos** theory has been proposed for generating an arrow of time in CM but it is still deterministic. The probabilities are coming from the uncertainties in the particle trajectory but are not inherent to the physical laws.

Quantum mechanic

QM fulfils the 1st and 2-a criteria. Changes are inherited from the quantum fluctuation of the vacuum. QM is also non-deterministic: there are many possible paths for the particle. But there is **no inherent mechanism for selecting one state**: the measurement process (human relevant) in Copenhagen interpretation of QM selects one state but as previously emphasized, this view requires two separated worlds: classical and quantum. The decoherence process does not select one but several states (diagonal in the ρ density matrix). The selection of one state requires add-ins to QM like the many worlds theory or the consistent history for a group of states. In the many worlds theory, the loss of information is due to our inability to be conscious of all the worlds which is very questionable. So QM is not able or at least has difficulties to generate an arrow of time.

Arrow of time in e-QM

In e-QM, **changes** are generated by the quantum fluctuations of the vacuum. As explained in the 1st section, a particle moves on left/right, up/down... in space and forward/backward in time due to the Brownian motion. The time here is the mathematical time used in our physical laws: un-oriented and reversible time named c-time to differentiate it from the irreversible time we are experiencing everyday. e-QM is **non-deterministic**: due to the forward and backward path, the particle could be in several space locations at the same time. A probability is associated with each location. **One state is selected by the decoherence mechanism** in e-QM: either when the particle interacts with another particle or when the environment blurs the phase. The loss of information and therefore the irreversibility and the time's arrow emerge in e-QM even for a single particle interacting with another particle or with the environment. Let us clarify the two times (c-time and e-time) in e-QM.

With the c-time only, the time's arrow cannot be explained. The particle interacts with the vacuum and creates the wave function. It happens the particle interacts with other particles and loses its phase (either through a measurement process or through the many small interactions with the environment). As pointed out previously, the particle decoheres and is localised at one space-(c-)time point. This decoherence (loss of information) increases the entropy [ref. 7]. The entropy is always increasing and this is our usual time, named **e-time** for entropy or emerging time. A particle interacting with the quantum vacuum stays quantum but if it interacts with another particle, it will lose its orientation and then appear as localised.

The entropy S (e-time) is always increasing, no matter if c-time is forward or backward as explained below. At t_0 the particle is in A. Due to the quantum fluctuations, it moves up to t_1 where it interacts with another particle. It decoheres and starts from its new location (see Fig. 12-a).

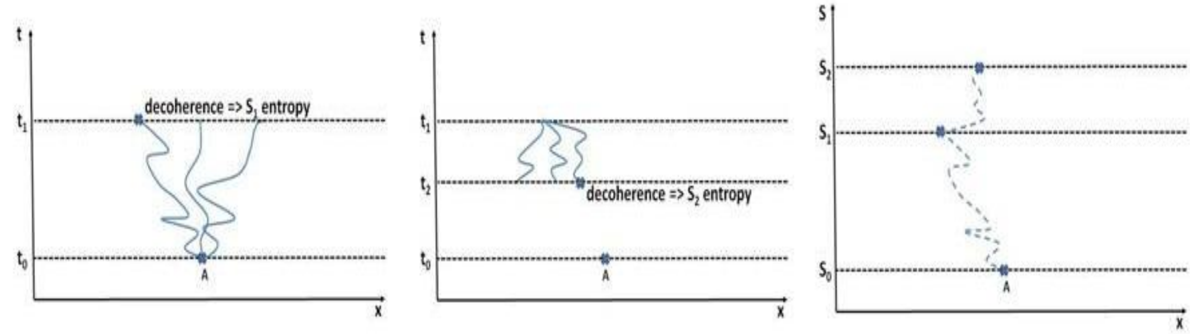

Figure 12: a) the particle decoheres at t_1 b) and then decoheres again at $t_2 < t_1$ c) with S as time

Moving backward in time, it goes to t_2 where it decoheres again after another interaction: t_i does not always increase (Fig 12-b) but the entropy S_i is always increasing. Figure 12-c shows the particle path with the appropriate e-time/entropy axis. The path is not defined in-between the decoherence points.
Our time is the entropy or e-time; it is always increasing. There is no grand-father paradox since we cannot move backward in e-time. We must emphasize this arrow of time exist for at least two particles

and there is no need to rely on very peculiar initial conditions at the beginning of the Universe to explain our time's arrow.

Dimension of the spacetime

The trajectories in QM and in e-QM are fractal of dimension 2; the Hausdorff dimension is 2 [ref. 2, 3]. In order to add its contribution, the path must intersect itself in e-QM so only the spacetimes of dimension 4 have quantum laws [ref 12]. For dimensions greater than 4, the quantum laws do not emerge.

Law without law

If the Universe is emerging from nothing, not only the matter must emerge from nothing like the quantum vacuum fluctuation but the physical laws must also be emerging from nothing. Emergence from nothing must be a basic principle greater than beauty and simplicity to discover new unknown laws. The starting point must be the vacuum for the stuff and random walk for the physical laws. Physical laws are necessary simple and local and apply to the whole world avoiding the division between microscopic and macroscopic world (quantum versus classical or reversible versus irreversible). There is no place for extended objects (strings, branes) or for curved space-time (general relativity) at the fundamental level. They could only appear as emerging properties. Space, time and physical laws are emerging from nothing as we have shown for e-QM and for the time's arrow.

Conclusion

Dance with the time? Time is at the heart of unanswered questions in physic and in our life but time is also the essential element for solving the Quantum Mysteries as presented in this document. By using simple assumptions like "locality" and "no time orientation", the laws of QM are emerging naturally and the major issues like quantum to classical transition, the measurement problem, the wave collapse, the entanglement or even the origin of the probability law are fixed. Two notions of time are also defined at the fundamental level; the 1st time (c-time) is not oriented and it changes the state of a particle and the 2nd time (e-time) is emerging from the loss of information due the interactions. The e-time is the entropy and is always increasing; it is the origin of all time's arrows.

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