# EPR, time, irreversibility and causality

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**Abstract**

Causality is the relationship between causes and effects. Following Relativity, any cause of an event must always be in the past light cone of the event itself, but causes and effects must always be related to some interactions. In this paper, causality is developed as a consequence of the analysis of the Einstein, Podolsky and Rosen paradox. Causality is interpreted as the result of the time generation, due to irreversible interactions of real systems among them. Time results as a consequence of irreversibility, so any state function of a system in its space cone, when affected by an interaction with an observer, moves into a light cone or within it, with the consequence that any cause must precede its effect in a common light cone.

*Keyword*: EPR paradox; Irreversibility; Quantum Physics; Quantum thermodynamics; Time.

## 1 Introduction

The problem of the link between entropy and time has a long story and many viewpoints. In relation to irreversibility, Franklin [1] analysed some processes, in their steady states, evaluating their entropy variation, and he highlighted that they are related only to energy transformations.

Thermodynamics is the physical science which develops the study of the energy transformations , allowing the scientists and engineers to obtain fundamental results [2–4] in physics, chemistry, biophysics, engineering and information theory. During the development of this science, entropy has generally been recognized as one of the most important thermodynamic quantities due to its interdisciplinary applications [5–8].

Entropy variation is always related to the evolution of the state of any system, between its initial and its final states [6, 7]. There are many different approaches to describe irreversibility in any process [2–4], but entropy is the physical quantity which quantifies just the irreversibility [6, 7, 9, 10]. Classical thermodynamics is developed by using a small number of state variables [2–4], and, in non-equilibrium thermodynamics, the system is described by considering its subsystems [11, 12], under the assumption that each of them is in local equilibrium [5, 11, 12]. This last hypothesis is required in order to introduce the temperature as a measurable quantity [5, 11, 12]. So, $T\sigma = \sum_i J_i X_i > 0$ represents a measure of the dissipation, where $T$ is the absolute thermodynamic temperature, $\sigma$ is the entropy production density, i.e. the time rate of the entropy density, generated by an irreversible process, $J_i$ is the $i$-th heat or mass flow, and $X_i$ is the $i$-th generalized driving force for vector transport processes or for chemical reactions [13–15]. Moreover, recently, an increasing interest is growing in the analysis of the fundamental role of fluxes in thermodynamics, and natural systems [16–24].

Last, a scientific interest is growing in establishing a comprehensive approach to irreversible processes, based on microscopic analysis [5–7, 11, 12, 25–28].

In this context, a possible link has been proposed between the macroscopic approach to irreversibility and microscopic behaviour of a system [29], suggesting the consumption of free energy as the principle cause of far from equilibrium states. Consequently, the related entropy production is generated by the redistribution of energy, momentum, mass and charge [30].

The effort in developing a thermodynamic approach to real systems has led to a growing interest towards the concepts of potentials and availability, in order to consider time in the development of theoretical models [31].

Honig [32] developed the relation between time and entropy in irreversible processes, by considering the heat transfer through the border of any system. His approach considers the time, $t$, only as a parameter to represent the path that systems follow from their initial to their final configurations.

The concept of path, in a state-space, leads to consider a set of consequent and related events, one followed by another, caused by the previous one. But, this concept is the thermodynamic expression of causality. Indeed, causality is the relationship between causes and effects [33]. In physics, causality represents the flow of events such that the causes of an event must always be in the past light cone of the event itself, and always related to some interactions of the system. In special and general relativity, the light cone is the path that a photon of light, emitted by a single source, takes through spacetime [34, 35]. In special and general relativity, an effect cannot occur from a cause that is not in the past light cone of that event. Moreover, a cause cannot have an effect outside its future light cone [34, 35]. Consequently, an event cannot produce any effect, if it is outside of the future light cone of another event [36].

In the second law of thermodynamics, the arrow of time is defined. But, also, causality a direction of time [37], due to its connection between a cause and its effect: this property is just a feature of this physical theory. The connection between causality and entropy has recently been pointed out [37], with the consequence of defining time as the metric of causality. Moreover, time has been highlighted to be discrete in nature [37].

In this context, we must highlight that the definition and understanding of the nature of time is difficult, because any process is usually described from a time viewpoint. In Newtonian physics, time is a mathematical variable, but, it isn't something real [38]. Simultaneity and duration of phenomena are absolute: a duration is an abstract property of the whole. But, Einstein introduced a completely new approach to time in Relativity, where instants and durations are dependent on the observer. The physical universe is space-time, a mathematical space continuously filled with ideal clocks [38]. These clocks are all synchronized with respect to a given observer, that measures the duration of a phenomenon through two clocks located in the places where the phenomenon starts and ends. So, another inertial observer, in motion with respect to the first one, doesn't agree on the space-time coordinates of the same events; consequently, the same phenomenon has a different duration in relation to any observer. As a consequence of this distinction, the requirement of the definition of physical time emerges [38]. Following Bell [39] and Pauli [40], Brown [41] pointed out that clocks don't measure time, but their behaviour in relation to some aspects of space-time [38]. Consequently, physical systems evolve in the phase space following the path which increases entropy! But, all these results require a physical definition of time.

In summary, it seems plausible to study how to link together the concepts of time, irreversibility, and causality. The aim of this paper is to suggest a possible approach to link together the concepts of time, irreversibility, and causality, by starting from some considerations on Einstein, Podolsky and Rosen (EPR) paradox.

To do so, we develop the analysis of time in relation to its physical definition as an atomic footprint of irreversibility, due to interaction between atomic electrons and environmental electromagnetic fields (photons). Consequently, a hypothesis emerges: only duration has sense in relation to the physical time originated from this footprint, related to the entropy variation due to the interaction. So, if the system is subjected to reversible processes, the irreversibility footprint disappears and time (as a duration of the interaction) becomes null. Thus, in completely reversible processes the systems move only in the space component of the space time, without having any movement in the time components. So, any completely reversible system seems to be able also to disappear in a space position and to appear in any other space position, without spending time. Furthermore, two reversible systems seem to interact with an infinite space range, because we cannot measure time until the entropy production is fully generated.

# 2 Materials and Methods

Since 1927, Bohr developed the principle of complementarity, a fundamental theory of quantum mechanics, based on observation and measurement [42]. The principle points out that, considering two quantum systems A and B, the measurement on one of them, for example A (or B), involves a physical interaction with the experimental setup, that affects both systems. This phenomenon is uncontrollable, even if it can be predicted statistically.

Since 1935, Einstein, Podolsky and Rosen developed some criticisms on the Bohr results. The EPR paradox presents some consequences on the foundation of quantum mechanics, even if many other interesting problems were originated by this criticism. In particular the problem of the collapse of the wave function, which represents a current open problem.

In order to develop our approach, we must introduce some statements from mathematics of quantum physics [43]:

- Let $\mathcal{X}$ be a vector space. Any finite linear combination of vectors $x \in \mathcal{X}$, $\sum_i \alpha_i x_i$, with $\alpha \in \mathbb{R}$, is named *convex*, if $i \in [0, 1]$ and $\sum_i \alpha_i = 1$.

- If $\mathcal{C}$ is convex, an element $x_e \in \mathcal{C}$ is called *extreme*, if it cannot be obtained as $x_e = \lambda\, x + (1 - \lambda)\, y$, with $\lambda \in [0, 1]$, $\forall x, y \in \mathcal{C} - \{x_e\}$.

- Let $\mathcal{H}$ be a separable Hilbert space. Let $\mathcal{S}(\mathcal{H})$ be a convex subset of $\mathcal{H}$. The extreme elements in $\mathcal{S}(\mathcal{H})$ are called pure states, while non-extreme states are named mixed states, or non-pure states.

- Schmidt's decomposition theorem [44]. Any pure state $|\phi\rangle$ can be written as a sum of orthonormal unit vectors $|u_i\rangle$ and $|v_i\rangle$, which span the space of possible-state vectors for the system, and $i$ runs up to the smaller of the dimensions of the two subsystem Hilbert spaces:

$$|\phi\rangle = \sum_i c_i\, |u_i\rangle \otimes |v_i\rangle \qquad \text{(A1)}$$

where $c_i \in \mathcal{C}$.

In 1935 [45], Schrödinger introduced the definition of entangled states, as the quantum pure states, $|\Phi\rangle$, from an ensemble of systems, that cannot be represented by tensorial products of eigenstates of the states themselves, which analytically results:

$$|\Phi\rangle \neq |\phi_1\rangle \otimes |\phi_2\rangle \otimes \cdots \otimes |\phi_n\rangle \tag{1}$$

where $\otimes$ is the tensorial product, and $|\psi\rangle$ are the states in the Hilbert space $\mathcal{H}$. A state is entangled if and only if it cannot be factorized.

During a measurement, a full wave function $|\Phi\rangle$ collapses into an eigenstate, $|\phi_i\rangle$, of the state bases, such that [46]:

$$\begin{aligned} \langle\Psi|\,|\psi_i\rangle &= 1 \\ \langle\Psi|\,|\psi_j\rangle &= 0, \forall j \neq i \end{aligned} \tag{2}$$

These relations express analytically the effect of the interaction between the system and the experimental set up.

Recently, the definition of time [29, 47] has been introduced by considering an analysis of photon-atomic-electron interaction, in relation to the irreversibility [48–50] based on an engineering thermodynamic viewpoint [51–54]. Time is conjectured to be related both to the entropy production and to the entropy production rate: this result agrees to the approach of Planck and Einstein, who have pointed out that the law of system evolution is precisely the law of evolution of entropy [55, 56]. The problem to link the macroscopic approach to the microscopic one is of interest in the various physical problems; indeed, it has been pointed out that macroscopic and microscopic approaches are two complementary tools [57], for studying the complex problems, where both the approaches coexist [5–7], as, for example, the relations between quantum mechanics and classical physics, matter-radiation interaction, electrodynamics of the Wheeler-Feynman model, nanothermodynamics, etc.

The starting considerations of our approach can be summarised as follows:

- The atom, without interaction, can be considered an isolated system, and any process inside it is completely reversible;
- The atom, in interaction with a photon, is an open system, where fluxes occur: in this case, a photon can be absorbed, and the atomic electron can have an energy level transition, then the electron can jump down in its fundamental energy state, with a related photon emission: the system is subjected to inflow and outflow of photons;

- The atom in interaction is subjected to the irreversible process of the perturbation of its center of mass: this open atom is irreversible, just because it is in interaction with the environment, and it is subjected to fluxes.

At atomic level, photons can be absorbed by the atomic or molecule electrons, and an electronic energy transition occurs between the energy levels of two atomic stationary states. Then, the photons can also be emitted by the excited electrons when they jump down into the energy level of the original stationary state. During this phenomenon, the electrons seem to follow a reversible energetic path, because they come back to the original stationary state of low energy level [58–62]. Indeed, when we consider a single atom or molecule, the energy perturbation of the center of mass is of the order of $10^{-13}$ J, while a usual energy for the electron transition, between two atomic or molecule levels, is of the order of $10^{-8}$ J, with an excited state lifetime of the order of $10^{-8}$ s [61]. Consequently, this approximation (not considering the effect of the atomic nucleus) is usually introduced. But, we stress that it is only an approximation [58–62], that cannot be considered in the analysis of the irreversibility, because it requires some considerations just on the role of the nucleus, during the photon-atomic electron interaction [51–53, 63]. As a consequence of the interaction between the atomic or molecule electron and the photon, a footprint occurs in the atom or molecule. The results obtained in Refs.[29, 51, 52] point out that the interaction between a photon and an electron in an atom affects the energy level both of the electron and of the center of mass of the atom in accordance with the theoretical and experimental results summarised in Refs. [48–50, 62, 64]. So, the macroscopic irreversibility is the result of the microscopic irreversibility due to the photon-electron interaction, which is the interaction between the environmental electromagnetic waves and the matter. Following the results obtained in the thermodynamic analysis of electromagnetic fields [65], this interaction can be expressed in terms of the entropy production, and of the entropy production rate. But, the ratio between the entropy production and the entropy production rate is a time. In analogy with analytical mechanics, where position and velocity can be used as independent variables for the state space, we introduce the entropy production $\sigma$ and the entropy production rate $\Sigma$, as the independent variables of the state space $\Omega = \{(\sigma, \Sigma)\}$, used to study the behaviour of the photon-atomic electron interaction. So, we can introduce the definition of time as follows [47, 66]:

$$\tau = \frac{\sigma}{\Sigma}, \tag{3}$$

Now, the entropy production rate can be written in relation to the electromagnetic waves as follows [65]:

$$T_0\,\Sigma = \frac{A}{2}\varepsilon_0 c E_{el}^2 + \frac{A}{2\mu_0} c B_m^2, \tag{4}$$

where $E_{el}$ is the electric field, $B_m$ is the magnetic field, $c$ is the velocity of light, a universal constant in the Universe, $\varepsilon_0$ is the electric permittivity in vacuum and $\mu_0$ is magnetic permeability in vacuum, $A$ is the area of the border of the thermodynamic control volume, and $T_0$ is the environmental temperature. The entropy production can be related to the analysis of irreversibility [48–50] of the interaction between a photon and an atomic electron [47, 66]. Here, the fundamental results are summarised in order to be used in the thermodynamic analysis of EPR paradox. To do so, we consider a photon which incomes to the atomic electron. For simplicity, we consider a Hydrogen-like atom, which is an open system from a thermodynamic viewpoint. The incoming photon has an energy $E_\gamma = h\nu$ and a momentum $\mathbf{p}_\gamma = h\nu\mathbf{u}_c/c$, where $h = 6.62607004 \times 10^{-34}$ J s is the Planck constant, $\nu$ is the frequency of the electromagnetic wave, $\mathbf{u}_c$ is the versor of the speed of light, and $c = 299792458$ m s$^{-1}$ is the speed of light [67]. If the photon has a frequency $\nu = (E_f - E_i)/h$, being $E_i$ the energy of the ground state of the electron, $E_f$ the energy of the excited level, the electron absorbs the photon and jumps from the ground state into an excited energy state. After the lifetime of this state, on which some considerations have previously been introduced, the electron jumps down into the fundamental state, emitting a new photon. There exists a change in the kinetic energy of the center of mass of the atom, but its amount ($10^{-13}$ J) is usually negligible in relation to the energy change ($10^{-8}$ J) in electronic transition and its time of occurrence ($10^{-13}$ s) is greater than the time of electronic transition ($10^{-15}$ s) [51, 61, 68]. However, if we develop a thermodynamic analysis of irreversibility, we must take into account this effect, so that the final energy of the atom, after the photon absorption, results [51, 61, 68]:

$$E_f = E_i + h\nu - \frac{h^2\nu^2}{2Mc^2} \tag{5}$$

where $M$ is the mass of the atom, and, in an analogous way, when the photon is emitted, it results [51, 61, 68]:

$$E_i = E_f - h\nu - \frac{h^2\nu^2}{2Mc^2} \tag{6}$$

Consequently, we expect an energy footprint in the atom [51, 52, 68], because, considering the effect on the center of mass, the interaction, between a photon and an electron in an atom, affects both the energy level of the electron and the energy level of the center of mass of the atom. Here, we stress that this effect is well known in quantum physics [61], even if the approximation of neglecting it is usually accepted, because of the small energy contribution of the center of mass. The quantum state function, after this interaction, solution of the Schrödinger equation, can be obtained by the usual quantum mechanical approach [67, 69]. So, it was analytically shown that the macroscopic irreversibility is the consequence of the microscopic irreversibility due to the interaction photon-electron, or from a macroscopic point of view, between the electromagnetic waves and the matter.

The fundamental state function, before the interaction, solution of the Schrödinger equation, can be obtained by the quantum mechanics [67, 69]:

$$\psi(\mathbf{r}, \mathbf{R}) = \phi(\mathbf{r})\, \vartheta(\mathbf{R}) \tag{7}$$

where $\phi$ is the wave function of the electron, $\mathbf{r} = \mathbf{r}_N - \mathbf{r}_e$ are the relative coordinates, with $\mathbf{r}_N$ the coordinates of the atomic nucleus and $\mathbf{r}_e$ the coordinates of the atomic electron, and [51, 52, 68, 70]:

$$\begin{aligned} \vartheta(\mathbf{R}) &= \frac{1}{(2\pi)^{3/2}}\ \exp(i\mathbf{k}\cdot\mathbf{R}) \\ \mathbf{k} &= \sqrt{\frac{2M}{\hbar}\, E_{CM}}\ \mathbf{u}_{CM} \end{aligned} \tag{8}$$

where $\mathbf{u}_{CM}$ is the versor of the nucleus momentum, $E_{CM} = \mathbf{P}^2/2M$ is the kinetic energy of the center of mass, $\mathbf{R} = (m_N\mathbf{r}_N + m_e\mathbf{r}_e)/(m_N + m_e)$ is the coordinate of the center of mass before photon-atomic electron interaction, $M$ is the total mass of the atom, $m_e$ is the mass of the electron and $m_N$ is the mass of the nucleus, $\mathbf{P}$ is the momentum of the center of mass, $\hbar = h/2\pi$ where $h$ is the Palnck constant, and $\mathbf{u}_{CM}$ is the versor of the momentum of the nucleus. Then, the photon incomes to the atomic electron, which jumps from the fundamental state into an excited energy state, and then it jumps down to the fundamental state, with the emission of a new photon. The fundamental state function, after this interaction, solution of the Schrödinger equation, can be obtained by the quantum mechanics [29, 51, 52, 61, 67, 69]:

$$\psi_f(\mathbf{r}, \mathbf{R}) = \phi(\mathbf{r})\, \vartheta_f(\mathbf{R}) \tag{9}$$

with $\phi$ wave function of the electron and [51, 52, 61, 68]:

$$\begin{aligned} \vartheta_f(\mathbf{R}) &= \frac{1}{(2\pi)^{3/2}}\ \exp(i\mathbf{k}'\cdot\mathbf{R}) \\ \mathbf{k}' &= \sqrt{\frac{2M}{\hbar}\, \big(E_{CM} + \frac{m_e}{M}\, E_{ph}\big)}\ (\mathbf{u}_{CM} + \mathbf{u}_c) \end{aligned} \tag{10}$$

where $E_{ph}$ is the energy of the incoming photon, and $\mathbf{u}_c = \mathbf{c}/c$ is the versor of propagation of the electromagnetic wave, with $\mathbf{c}$ the velocity of light and $c$ its value. A quantum thermodynamic approach to this photon-atomic electron interaction, allows us to prove that this atomic process leaves the footprint [29, 51, 52]:

$$E_{ftp} = \Delta E_{ph} = \Delta E_{CM} = \langle \psi(\mathbf{r}, \mathbf{R}) \, |\mathcal{H}| \, \psi_f(\mathbf{r}, \mathbf{R}) \rangle = \frac{m_e}{M} \, E_{ph} \tag{11}$$

where $\mathcal{H}$ is the Hamiltonian of the photon-atomic electron interaction, i.e. from a macroscopic point of view, the interaction between electromagnetic wave and matter. Then, it is possible to evaluate the entropy production as follows [29, 51, 52]:

$$T_0 \sigma = \frac{m_e}{M} \, E_{ph}. \tag{12}$$

So, the definition of time, in relation to irreversibility, results:

$$\tau = \frac{2 \, m_e}{M \, c} \, \frac{E_{ph}}{\epsilon_0 \, E_{el}^2 + \mu_0^{-1} \, B_m^2} \tag{13}$$

Some considerations may be introduced [71]:

- Time is the result of the irreversibility;
- Locally, entropy can decrease, but the entropy production (due to irreversibility) must always increase, with the consequence that time can only increase.

# 3 Results

Now, in relation to the definition of time, some considerations can be introduced [72]:

- The definition of time (13) is related to the entropy production, and the variation of this quantity is extended to any epoch and domain, since the Universe formation, because any process generates an entropy variation;
- The definition of time (13) is linked to entropy variation and fluxes;
- The present physical scales might be extrapolated into the past by considering the entropy and the temperature of any epoch of the Universe, its formation included;

- The definition of time (13) is related to a duration, so, it satisfies the requirement of Einstein that any definition of time must be related to a clock.

Moreover, local time flow rate is different in relation to global Universe time flow rate, because global Universe flow rate is the global effect of the entropy rate generation, while the local time follows the distribution of the local entropy variation and rate, in accordance with the Theory of Relativity.

In relation to the EPR paradox, the results can be summarised stating that without any interaction, time cannot exist, as previously suggested, as a consequence of the interaction between electromagnetic waves and matter.

Now, following the original EPR gedanken-experiment [73], we consider two spin-1/2 particles, generated by the same source, A and B, which move in opposite directions. These particles can be detected only if they interact with an experimental setup. Until they interact, from the previous considerations, they are only in spatial dimensions, because time flow starts only from their interaction with an observer. So, independently by their distance, the two systems *are not aware* of being separate, because they aren't subjected to time dimension. Before the interaction with the observer, their state function is [70, 74]:

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(\left|\frac{1}{2}\right\rangle_{\mathrm{A}}\left|-\frac{1}{2}\right\rangle_{\mathrm{B}} - \left|-\frac{1}{2}\right\rangle_{\mathrm{A}}\left|\frac{1}{2}\right\rangle_{\mathrm{B}}\right) \tag{14}$$

So, as a consequence of the interaction of one of the particles with the set up, the state function collapses into a particular value, determined by the interaction itself, and, as a consequence of the interaction, also time begins to flow. When the particle interacts with the set up, its energy, $E$, is known with a small value of uncertainty $\delta E$, related to the set up considered. But, the Heisenberg's uncertainty principle:

$$\delta E\, \delta t \geq \hbar \tag{15}$$

states that time cannot be determined with the same accuracy [69], being $\delta E = \sqrt{(E - \langle E\rangle)^2}$ and $\delta t = \sqrt{(t - \langle t\rangle)^2}$. The different values of time are distributed around the origin of time, following the probability [69]:

$$|\phi|^2 = \frac{1}{\sqrt{2\pi}\, c\delta t}\, \exp\left( - \frac{t^2}{2\,(\delta t)^2}\right) \tag{16}$$

being $\langle t\rangle = 0$, in our discussion. So, during the collapse, the particles can influence each other, because still outside of time as we can detect, up to the end of the interaction, so, for example [70]

$$|\phi\rangle_A = \left|\frac{1}{2}\right\rangle \Rightarrow |\phi\rangle_B = \left|-\frac{1}{2}\right\rangle \tag{17}$$

In our opinion, time, as we usually measure it, can be detected only after the interval $\delta t$ from our reference frame. So, $\delta t$ is what an observer senses in his/her reference frame, which corresponds to the entropy production $\sigma$, just required to generate the time interval itself. During this entropy production the particles influence each other.

The results obtained confirm the Bohr approach, but highlight also the fundamental role of the space-time, obtained by Einstein, and the recent relation between time, causality and space-time [75]. Indeed, the proof suggested points out that the conditioning of the measurements is due to the zero value of the time dimension, unless one of the system interacts with the experimental setup. Consequently, it follows how irreversibility represents a constraint in the interactions, conditioning the behaviour of correlated systems.

Thus, causality, as seen by an observer, is related to the time generation due to irreversible interactions of real systems among them. If the events are correlated at the start, independently from their location, they maintain their correlation, while if they aren't correlated, they could be correlated only after an interaction. In particular, Equation (13) points out that, without interaction, time doesn't exist, so, it would be impossible to observe an order in the events. But, after any interaction, time occurs and the order of the events can be pointed out. Consequently, also the relations between two events can be highlighted, with particular regards to their causal relations. Moreover, in the theory of special relativity, causality is related to simultaneous observer-dependent [76]. Consequently, following special relativity, the cause must precede its effect in accordance to all inertial observers; moreover, in general relativity, the effect must belong to the future light cone of its cause, even if the space-time is curved [34]. These statements mean that the cause and its effect are separated by a time-like interval, and the effect belongs to the future of its cause [34]. Here, we conjecture that time interval is originated only during the interaction between a system and an observer, so a time-like interval occurs only after this interaction. So, before this interaction, all the systems are in a 'contemporary' state.

# 4 Discussion and Conclusions

In Newtonian physics [77], an effect cannot occur before its cause [78]. In Special and General Relativity this statement has been improved by stressing that an effect cannot occur from a cause that is not in the back light cone of that event [79]. These results are the consequence of finite speed of light, and that the speed of light is the maximum velocity in our Universe Consequently, no information can be transferred at a velocity higher than the light speed.

Moreover, the concept of causality has deeply been improved by relating it to the meaning of the simultaneous observer-dependent [80], which states that the cause must always precede its effect in accordance with all inertial observers. Consequently, the cause and its effect are separated by a time-like interval in the space-time [79, 80] and a signal could be changed between these two related events at less than the speed of light.

Then, in quantum field theory, causality is closely related to the principle of locality, which is still under study because it depends on the interpretation of quantum mechanics, with particular regards to quantum entanglement and Bell's Theorem [81]. Recently, in causal dynamical triangulation [75], causality has been related to the foundation of the space-time geometry [82].

All these viewpoints can be summarised by the results here obtained. Indeed, in relation to the link between the thermodynamic statistical analysis of the irreversible paths and their stochastic order [83], the energy flow, between systems and their environment, have been shown to select and shape the paths [17, 19–24, 84–87]. As a consequence of this interaction, irreversibility occurs also at the atomic dimension. But, just this result allows us to approach the problem of causality, by starting from the analysis of the EPR paradox. In this way, time is the consequence of the causality, which is the result of a sequence of ordered events, but also of irreversibility; indeed, the continuous interactions, between the atomic electrons and the electromagnetic waves in the environment, causes the non-equilibrium state of our Universe [30, 53, 63, 66, 71, 72, 88].

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