# Do quantum theories point to an elsewhere of space-time?

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## Abstract

Quantum realities seem to call for the existence of an elsewhere of spacetime. Examples taken from Quantum Mechanics, Quantum Field Theories and Bell's type experiments point to this disconcerting conclusion. How such an elsewhere can be thought of is the question addressed in this paper. How can quantum realities stand outside of spacetime, and if they do so what does it mean to enter spacetime? This conundrum can be fixed by focusing on the nature of quantum realities as it is revealed within the above three domains. Prospects are introduced in a gradual way and converge to what can be taken as a synthetic and universal characterisation of this spacetime's elsewhere.

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## I. INTRODUCTION

Quantum entanglement is no doubt one of the most emblematic phenomena displayed by quantum physics, separating it from classical physics in a radical way. Remarkably, at least when the number of degrees of freedom involved in a quantum system is not too large, the quantum formalism allows one to derive the phenomenon in a simple manner, given the fundamental *superposition principle* of quantum mechanics. This is what Schrödinger did in 1930. Now, Schrödinger found entangled states so bothering that he decided not to think of them any longer and it is not before the 1960's that physics got in touch with entangled states again [1].

The matter with entangled states whose physical reality was to be checked at an experimental level is that measurements performed on them seem to conflict with the *locality* of physical laws, *i.e.*, with the fact that according to relativity theory no physical influence should propagate at a speed greater than $c = 3 \times 10^8 m/s$, the speed of light waves in the vacuum.

However, cumulated experimental data pointed to the evidence that the light speed limit was superseded by factors of at least 50.000 in order to possibly account for the propagation speed of quantum correlations within pairs of two entangled particles for example [2].

In the past few decades such a state of affairs had taken physicists to express the idea that quantum mechanics ($QM$) and relativity theory were, at best, living in a peaceful mode of co-existence; and shortly afterwards, to opt instead for an interpretation of quantum mechanics in terms of *non-locality*, positing at the same time that this non-locality wouldn't contradict relativity [3].

Be it as it may, what is clearly questioned with the *Bell's type experiments*, probing quantum correlations between entangled pairs of particles, is the intriguing set of relations to space and time that quantum correlations put forth. This is the very concern of the current paper.

As it is often the case in science when unexplained or paradoxical phenomena show up, it is instructive to investigate whether similar, albeit less dramatic trends, were already prevalent in the corpus of previous knowledges, that is, here, in quantum physics.

The current analysis will accordingly begin with some survey of standard quantum mechanics in next Section II. The quantum world however is not ruled by the universal constant $\hbar$ alone but by the two universal constants $\hbar$ and $c$, in an inseparable manner [1]. And still, there is more to it. Another crucial ingredient, the *field* concept proves indispensable in order to explain experimental data at an unprecedented degree of accuracy. This is why it will be essential to recall the aspects of relations to spacetime that relativistic theories of quantum fields, $QFTs$ for short, make manifest [4]. This will be done in Section III. Then, Section IV will consider the recently argued closure of Bell's type experiments loopholes. In all three Sections the relations to spacetime are questioned. A final Section V presents the conclusions that can be drawn from the three cases analysed and a synthetic identification of this elsewhere of spacetime is proposed.

## II. FROM QUANTUM MECHANICS ($QM$)

In $QM$, the status of the wave-function has been the matter of long and ongoing debates [5]. This issue has been analysed thoroughly in [6]. For our current purpose a few points need to be recalled. They will be presented in as concise a way as possible. Some precisions will also be brought to the matter whenever necessary.

### A. Two levels of the physical reality: Actual and potential

For a quantum system the knowledge of its wave function allows one to calculate all of the physical properties of the system, its *observables*, their evolution in time being controlled by the Schrödinger equation. And so it is important to elucidate the *ontological* status of such an efficient tool as the wave function is, formally, a vector in some abstract linear space over the complex field of numbers, $\mathbb{C}$.

Would the wave function be the only and complete knowledge one has about the quantum system, which, after all, experimenters do prepare, as most physicists and philosophers tend to think nowadays? Or is there a more profound relation to the nature of the quantum system its wave function describes so well?

These two questions target two different approaches to the quantum reality. That of

[1] The *spin* is a striking example. Proportional to $\hbar$ and requiring Lorentz invariance ($c < \infty$) rather than Galilean invariance ($c = \infty$) in order to comply with experimental facts [7].

*pragmatist* physicists who are satisfied with the formalism efficiency [8], and that of physicists who do not renounce the hope to lift the veil on the physical reality underlying $QM$ to make more rational sense of the enigmatic quantum world [9]. One may think that this second family is aware that all physics is based on, and calls for philosophical reflections [10].

To sum up, the debate testifies to an *epistemological-versus-ontological* tension concerning the status of the $QM$ wave function, the synthesis of which relies on a proposed ontological understanding of the quantum nature [6].
A simple wave-function like,

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|D_2\rangle + i|D_1\rangle\right] , \tag{1}$$

describes a quantum optics experiment where 'a photon' [3] emitted from a source at an instant $t_0$, propagates towards a horizontal beam splitter by which, with equal probabilities, the photon will be either transmitted (symbolically represented by the state vector $|D_2\rangle$) or reflected (state vector $|D_1\rangle$). The photodetectors $D_1$ and $D_2$ are located at an equal distance to the beam splitter. After a lapse of time, $t > t_0$, the wave function (1) is written as the equally pondered sum of the two possibilities 'the photon' has to propagate through this experimental device. This is depicted in Fig.1. Thus, (1) refers explicitly to the constrained possibilities 'the photon' has to propagate, that is to some inventory or *catalog* aspect of the wave function describing the elementary quantum optics experiment; and this accounts for the epistemological status of the wave function (1).

Now, be it at a formal level only, it is clear that (1) cannot be mistaken for a catalog, which should properly be written in terms of sentences, comas, semicolons and points. Furthermore, stating (1) and postulating unitary evolutions in the general case, cannot be exhausted by an interpretation in terms of catalog.

Much more than this, (1) is nothing less than an assertion that 'there is a something', an entity endowed with some persistence. At the very least in effect, (1) is the affirmation that *a unity* exists and persists under both unitary evolution.. *and* collapse [6]. This unity

[3] It is important to realise that the discourse, 'which path the photon has followed' is but a reconstruction, a reinterpretation *a posteriori* of the experimented physical reality. Before 'the click' on either of the two detectors $D_1$ and $D_2$, no photon, such as duly defined in $QFTs$, did ever propagate within the experimental setup [6, 11]. In the full rigour of $QFTs$, a photon, like any other elementary particle, is more '*une façon de parler*' than a sound physical localisable object. However convenient such an image may be to an empirical description of an experimental situation, this image remains essentially misleading.

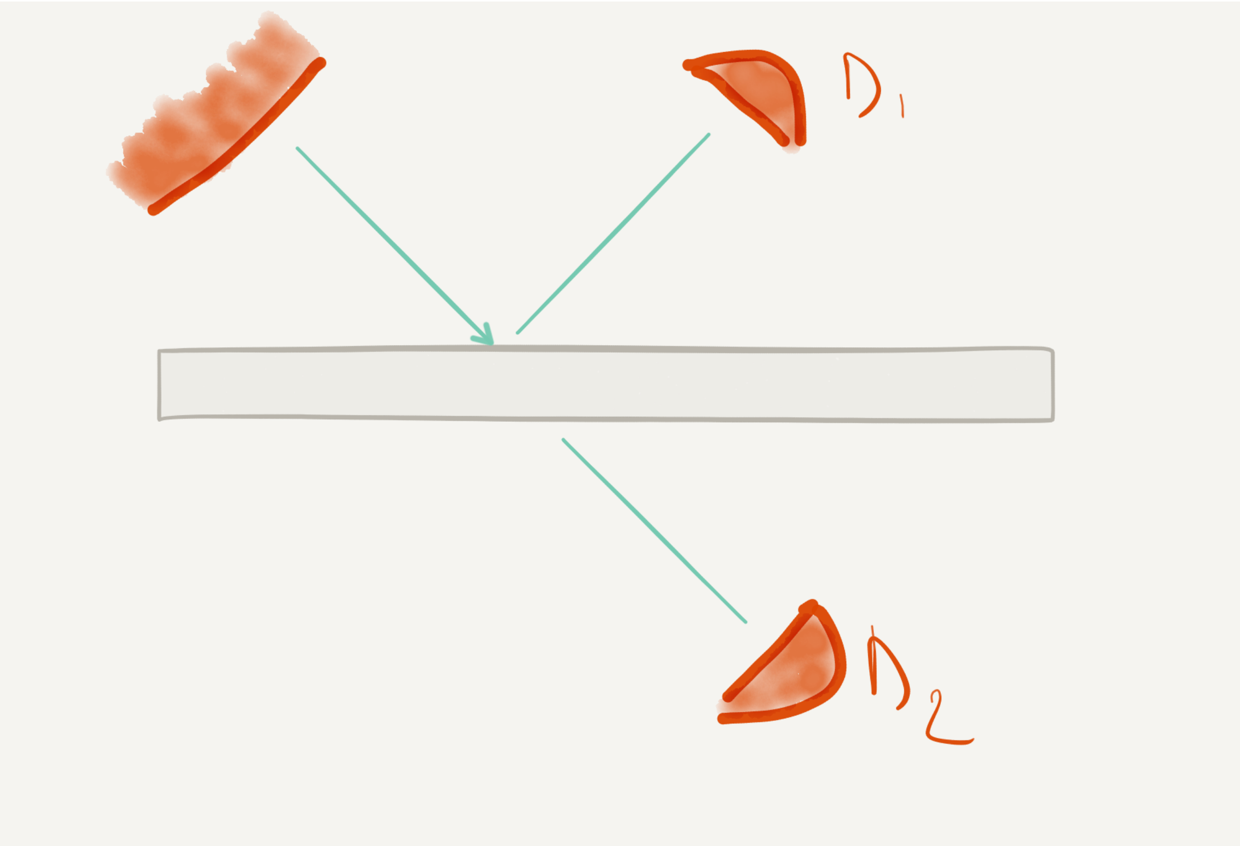


FIG. 1: A source emits a photon reflected towards a detector D1, or transmitted to detector D2 by a beam-splitter with equal probabilities (in front of $|D_1\rangle$ a factor of $i$ accounts for the case of reflection).

is supported by an entity, quantum, whose behaviour is such that it is adequately described by such a complex-weighted linear combination of possibilities. Taken as actualised, these possibilities are mutually exclusive, indicating that their linear combination can only refer to a potential mode of the physical reality, not to a physical actual realisation.

The interest of distinguishing between the reality of potential states from the reality of actual states, is that this distinction makes it possible to account for the relevance of the wave function *as it is*, its very structure testifying to 'the level of reality of what we talk about'. To emphasise this crucial point it matters to note that a purely epistemological wave function would not be able to account for the operational efficiency of the wave function description in all possible cases [12].

Two major points are at the origin of the long debated *epistemological- versus-ontological* tension concerning the wave-function, which cannot be overemphasised.

◇ In the first place, what is forgotten is the *crucial* statement that what is in a state of potency can never be apprehended *in itself*, but only through the actual realisations it is capable of. What a linear combination of various antinomic possibilities, moreover weighted with complex numbers (what is more [13]) finally means is that such a wave function refers to a potential mode of the physical reality. One can check that a number of reputed bizarre cases of Quantum Mechanics can be revisited and elucidated along these lines of thinking [6].

◇ In a second step, the 'only mystery' aspect of the superposition principle [4] follows when one realises that in physics, as it is commonly practised with measurable objects, the reality of potency is simply denied. Only what is measurable/observable is taken for physical and real. In quantum field theories, a cogent expression of this attitude has been coined by D. Mermin's famous quotation that *correlations only have a physical meaning/reality, what they correlate does not.*.[14].

In short, not until the proper ontological status of quantum entities is duly recognised, can the epistemological and ontological aspects of the wave function be reconciled, that is properly ordered the one with respect to the other in a rational manner [6].

### B. Relations to space and to time

#### *1. To space*

Spacetime is the very consideration of *relativity theories*, special and general, which define it as a differentiable manifold, that is as a smooth enough set of *event-points* endowed with a convenient topology. Locally, in the neighbourhood of any point, this smooth set of points is isomorphic to the well known Minkowski spacetime, with metric $g_{\mu\nu} = diag(1, -1, -1, -1)$, which is a flat $4D$ spacetime (zero curvature).

In situations which can be adequately be treated within ordinary $QM$ though, relativistic spacetime considerations are largely absent [5]. The position $x$ acquires the status of an

[4] The superposition principle has been called 'the only mystery' of quantum physics by R.P. Feynman.

[5] This is why ordinary $QM$ is sometimes regarded as a $QFT$ on a 1+0 dimensional manifold, as compared to the $QFT$s composing the *Standard Model of Elementary Particles* which are theories on $1+3$ spacetime manifold.

operator, $\widehat{x}$ say, as is obvious on the most famous quantisation rule,

$$[\widehat{x}, \widehat{p}] = i\hbar\,, \tag{2}$$

where the momentum $p$ is itself an operator, $\widehat{p}$, on the system's Hilbert space of states. Now, the $QM$ formalism provides us with a consistent and meaningful relation, which is

$$\Psi(x) =< x|\Psi > \ . \tag{3}$$

This means that the value at location $x$ of the wave function describing a $QM$ system is obtained by a *projection* on the state vector $|x>$, which is an eigenstate of the position operator,

$$\widehat{x}|x >= x|x > \ . \tag{4}$$

This relation is of utmost interest. It manifests clearly that, *in itself*, the wave function $|\Psi>$ has no definite space location before its projection on a given location state vector $|x>$ is achieved.
This point may look purely formal, something like a convenient notation or a technical nicety. But there is more to it for at least two reasons. The first reason is that position is a plain operator $\hat{x}$ with the experimental counterpart of so-called *tomographic methods* which 'scan' the wave-function over the whole space according to (3) [6]. A second reason is that the remarkable adequacy of the $QM$ formalism to the quantum phenomena does not happen just by chance: It finds remarkable philosophical roots in the quantum physical reality itself [6].

*2. To time*

Not surprisingly, $QM$ being not a relativistic theory, the situation for time is different. While position can consistently acquire the status of an operator, $x \to \widehat{x}$, no equivalent

[6] In order to deal with quantum issues, physicists have been led to enlarge the mathematical apparatus in the direction of increasing degrees of abstraction, inducing the idea that physics was itself more abstract, i.e., further removed from reality. A philosopher like J. Maritain, for example, proposed to look at theoretical physics as an art of understanding reality through *verified myths* [15]. Now it is not because the mathematical tool is more abstract that the corresponding physics is itself further removed from reality. In fact, the opposite point of view reveals pertinent. Because this mathematical tool is better confirmed by reality, it shows us that reality is deeper than we understood it to be, when it was perceived through simpler mathematical structures. This point of view, somewhat met in [16], could be developed elsewhere.

relation holds in the case of time [13], in spite of various attempts in this direction. Time cannot be consistently implemented as an operator and remains a *parameter*, that of a temporal evolution whose differential form is given by the famous Schrödinger equation,

$$i\hbar \frac{d}{dt} |\Psi(x,t)\rangle = H |\Psi(x,t)\rangle \,, \tag{5}$$

where $H$ is the *Hamiltonian* of the system under consideration. The point here is that the temporal evolution prescribed by (5), formally known as *unitary*, involves that it is *reversible*.

It is in this $QM$ very context that the issue of *reversibility* showed up and has motivated an important scientific literature. The situation may be quickly summarised as follows.
The $QM$ master equation (5) ruling the time evolution of elementary quantum systems is linear, deterministic and time-reversible, whereas physics at any of the larger scales displays a *time-arrow* which cannot be inverted. Time flows in a single direction and a would-be fundamental time-symmetry is obviously broken. How is it that time symmetry is broken while being the rule at the elementary quantum scales is the question.

This issue needs not be discussed further because as evoked in the Introduction, it requires the larger and deeper formulation offered by the relativistic theories of quantum fields, the $QFTs$. There, the sound solution this issue receives is the famous $TCP$ theorem [17]. Any local Lorentz invariant theory must be invariant under the combined three discrete operations of *time-reversal*, $T$, *charge conjugation*, $C$, and *parity*, $P$, *i.e.*, reversal of spatial axes. This non-trivial theoretical statement, which experiments validate, establishes that the genuine *discrete* symmetry of quantum elementary processes is $TCP$ and not $T$ alone.

Getting back to the ordinary $QM$ case is interesting though. There, the unitary temporal evolution of a system's wave-function would only transform the probability amplitudes according to (5). For a simple example, in the case of a *time-independent Schrödinger equation*, where the Hamiltonian $H$ has no explicit time-dependence, one would have for the evolving wave-function,

$$|\Psi(0)\rangle = \sum_E a_E(0)|E\rangle \quad \longrightarrow \quad |\Psi(t)\rangle = \sum_E a_E(t)|E\rangle \,, \tag{6}$$

where $a_E(t) = a_E(0)e^{\frac{-iEt}{\hbar}}$ and where the eigenstate $|E\rangle$ are those of $H$, $H|E\rangle = E|E\rangle$ [7]. Because of the unitary evolution the norm of $|\Psi(t)\rangle$ is conserved, $\langle\Psi(0)|\Psi(0)\rangle = \langle\Psi(t)|\Psi(t)\rangle$,

[7] The Hamiltonian $H$ is here supposed to admit a discrete and non-degenerate spectrum, and the set of eigen-kets $|E\rangle$ supposed to form an orthonormal basis.

so that the evolution from $|\Psi(0)\rangle$ to $|\Psi(t)\rangle$ is tantamount to a complex rotation operating within the Hilbert space spanned by the orthonormal basis vectors $\{|E\rangle\}$.
In this case, evolution in time will leave the wave-function in the same state of potency as the wave-function state one started from, as is made formally clear by reading the evolution as a rotation in the Hilbert space of states which has no spacetime anchorage.
This means that not until a measurement is performed on the system, inducing some collapse of the linear superposition, can a dating be ascribed to the evolution of the quantum system which, then, has ceased to evolve in a unitary way; and by the same token, has also entered *temporality* in an irreversible *instantaneous* manner: That is, not in the manner of a *local movement*, which a mechanism, a history in spacetime, could account for [6].

⋄ This understanding of the issue has the advantage of clearly delimiting the domain of reversibility in $QM$, restricting it to the unitary evolution of linear superpositions only.

⋄ Accordingly, it isn't a genuine physical and actual reversibility, proceeding from measured processes, duly recorded in spacetime, whose time ordering could be inverted without any change, checking then what would define a genuine reversibility.

⋄ No conflict shows up either with the established time-arrow to which the whole set of *actual* elementary physical processes obey [7] and whose only genuine discrete symmetry is $TCP$.

Taking stock of the preceding paragraphs, things can be summed up in the following way.

- From (3) and (4), it is clear that the $QM$ formalism displays possible states of localisation that are 'prior' or 'before' the actual localisations that can be measured experimentally. Hence a kind of exteriority with regard to the spacetime of our world shows up, which may have led some physicists to doubt, *again*, that the wave-function describes more than our own epistemic understanding of a quantum system.

- From (6), it appears that the wave function remains in its state of linear superposition as *our* time flows by. This may have taken some physicists to think of a double temporality [19].

[7] Here may be the place where to contest a point of view expressed in a very deep analysis bearing on 'The Ontological Status of Quantum States' [18], where the following is expressed. *Note that the problem of 'actualization' of physical properties is not solved by the assumption of a wave-function collapse that reduces the quantum state to an eigenstate of the measured observable. Such a collapse does not* per se *alter the ontological status of this state, and thus the state of the system after the collapse cannot be regarded as more 'physically real' than before the collapse.* It *does* on the contrary, making a physical reality pass from a potential, non measurable mode, to a more actual mode, possibly measurable [6].

The evolution time of the linear superposition wouldn't be *our* time.

If instead the potentiality of the wave-function is properly taken into account [6], then the wave-function unitary evolution in our own time, as we can catch it, is but an expression of this potentiality, and there is no need to introduce any other temporality. Besides, from the point of view of *wave-functions' collapses*, we could recover again an appearance of exteriority with respect to our spacetime, because there is nothing to allow us to think of collapses in terms of mechanisms, that is in terms of *local* motions [6].

## III. FROM $QFTs$

The physical quantum world is not shaped by the universal Planck constant alone, $\hbar$, but by both $\hbar$ *and* the universal speed limit $c$, in such a way that it could be worth listing the series of relations through which the two constants are seen to call one another.

Suffice it here to recall that at 3 spatial dimensions, Lorentz invariance is a consequence of a causality axiom related to the existence of a *finite* speed limit, $c < \infty$ [20]; and that Lorentz invariance has also a definite quantum nature [21], while the $\hbar$- quantum physics pinpoints a fundamental speed limit as a consequence of the *non-cloning theorem* [22].

Now, it is important to recall that before the advent of Quantum Field Theories, attempts at formulating relativistic quantum theories have existed. However these theories didn't fit the experimental results of particles' scattering processes, and didn't even let room to a notion of localisable particles. After the universal constants $c$ and $\hbar$, a crucial concept was missing. In order to account for the physical reality, the concept of *field* turned out to be essential.

It has been proven that a field theory structure is called by both $QM$ and the theory of relativity for mutual compatibility and in order to let *partial* room to the notion of a localisable particle [23].

In the end, $QFTs$ are *relativistic theories of quantum fields* and have encapsulated these three elements into most successful theories, giving rise in particular to the *Standard Model* of particle physics. The aspects of potency met in $QFTs$ [4] are therefore worth revisiting.

### A. Quantum fields and potency

As just evoked, together with the fruitful concept of field [4], $QFTs$ integrate the physics of $\hbar > 0$ and of $c < \infty$ which are usually set to unity, $c = 1\,, \hbar = 1$ and accordingly not written. In order to wit, these constants are restored in the expression (7) below. The ensuing theories of Quantum Electro-Dynamics ($QED$), Electro-weak theory and Quantum Chromo Dynamics ($QCD$) have cumulated impressive series of successes in their confrontations with experiments and in their verified predictions concerning the existence and properties of particles that hadn't even been discovered yet.

Now, what is a quantum field?

A quantum field is a physical *quantum* reality whose formal expression, the corresponding [8] *quantised* field, is a mathematically elaborate construction, an operator valued *tempered distribution* on some relevant representation space of states (Hilbert, Fock, $KMS$, others,..). For example in $QED$, the photon field, quantised in the *radiation gauge* ($A_0 = 0,\ \vec{\nabla}\cdot\vec{A} = 0$) reads as ($i = 1, 2, 3$),

$$A_i(t,\vec{x}) = \sum_{s=1,2} \int \frac{d^3k}{(2\pi)^3\, 2\, c|\vec{k}|} \left[\varepsilon_i^{(s)}(\vec{k}) a_s(\vec{k})\, e^{-\frac{ic|\vec{k}|t}{\hbar} + i\frac{\vec{k}\cdot\vec{x}}{\hbar}} + \varepsilon_i^{(s)^*}(\vec{k}) a_s^\dagger(\vec{k})\, e^{+i\frac{c|\vec{k}|}{\hbar}t - i\frac{\vec{k}\cdot\vec{x}}{\hbar}}\right], \tag{7}$$

whose character of operator is that of the *creation* and *annihilation* operators $a_s^\dagger(\vec{k})$ and $a_s(\vec{k})$ respectively. They satisfy the quantisation rule of $[a_s(\vec{k}),\, a_{s'}^\dagger(\vec{k'})] = (2\pi)^3\delta^{(3)}(\vec{k}-\vec{k'})\delta_{ss'}$ and account for the possibility for photons to be emitted or absorbed, in agreement with established experimental facts.

In $QFTs$, one calculates the correlation functions of quantised fields such as (7) with itself and other fields, the so-called *Green's function*, out of which a complete access to all of the physical properties of the system, the observables, can be reached.

Now, again, what (7) displays is a generalisation of (1) in the sense that it is a continuous linear superposition of all possible photonic plane-wave physical realisations, with two ($s = 1, 2$) polarisation 3-vectors $\varepsilon_\mu^{(s)}(\vec{k})$ at wave-vectors $\vec{k}$, which are mutually exclusive of each

[8] Corresponding .. in view of a certain type of solutions to the field equations, in relation to the experimental measures. $QFTs$ do not exhaust the full span of quantum physics (See below, the end of this subsection).

others,

$$s, s' = 1, 2\,, \quad \varepsilon^{(s)}(\vec{k}) \cdot \varepsilon^{(s')}(\vec{k}) = \delta^{ss'}\,, \quad \int \mathrm{d}^4 x \; e^{-ik\cdot x}\, e^{+ik'\cdot x} = \delta^{(4)}(k - k')\,. \qquad (8)$$

This, like in the case of the $QM$ wave function, indicates that the physical reality corresponding to (7) is a physical and quantum entity, but in a state of plain potency, and thus, not itself measurable though a reality of the physical world. On the postulate that only measurable entities have a reality, this could be what lead D. Mermin to think that 'correlations only have a physical meaning/reality, what they correlate do not.', as quoted in previous Section II.

On the contrary, the detailed analysis of [4] argues that the 17 reported elementary quantum fields, corresponding to the 17 *measured* elementary particles, *do* exist as physical quantum realities, but in a mode of potency. They show up exactly as they are, that is, not as the resulting composition of any preliminary matter, field or any antecedent entity [9].

As a consequence of the peculiar ontological status of the elementary quantum fields, their associated elementary particles show up as *finite* energy excitations in the corresponding quantum fields (which can also be viewed as a *medium*, or 'a mattress' in the terms of [24]) to which elementary particles borrow their formal properties of spins, masses, polarisations.. One can note that this interpretation renders perfectly consistent and understandable the fact that in $QFTs$, elementary particles are read off their corresponding quantised field 2-points correlation functions, the so-called *propagators*.

In more intuitive terms, we could say that elementary particles, which are intrinsically quantum entities, are their corresponding non-measurable quantum fields made measurable; with, for the sake of rigour and completeness, the important proviso that quantum fields are capable of measurable realisations other than their corresponding elementary particles [25, 26], to which, it bears repeating, $QFTs$ offer only a partial space of identification [23].

### B. Elementary quantum fields and spacetime

There is no need now to differentiate spatial from the temporal variables because $QFTs$ are built-in *covariant* theories, as physicists call them with some abuses [10]. One no longer

[9] Certainly not a trivial statement at a philosophical level.

[10] For example the Kubo-Martin-Schwinger ($KMS$)-representations of the quantised fields' algebra describe $QFTs$ at non-zero Temperature and/or chemical potential. They can be given a *covariant* formulation

deals with space and with time but with spacetime. In $QM$ we have recalled that position in space, $x$, can consistently be promoted to the status of an operator, $\widehat{x}$, but that this promotion does not extend to the case of time.

In $QFTs$ now, none of them, $x$ or $t$ are operators, quantised fields only are, while $(t, x, y, z)$ are just numbers which tag the date and location of an event-point in a 4-dimensional spacetime manifold. In a $QFT$ theory, a system of free or interacting quantised fields is postulated to live in a given spacetime manifold $\mathcal{M}$, and so far there seems to be no efficient way to avoid or circumvent this practice in theoretical physics.

This state of affairs is generic of all $QFTs$. Right from the onset, any possible system of quantised fields is separated from the spacetime manifold on which the quantised fields' system is postulated to live. In a second step only, and based on physical considerations, the spacetime manifold can be taken to be Euclidean, Minkowskian or curved [27], with or without boundaries. One then calculates fields' correlation functions on these various spacetime manifolds. Not surprisingly, the fields' correlation functions calculated over various spacetime manifolds display results which differ drastically from each others [27, 28].

At this level therefore, which is that of formalisms, one cannot state in a more cogent manner that quantised fields are not in any spacetime *in the first place*. This must apply also to their physical pendents, the *quantum fields* which are not themselves measurable and which, as recalled in previous Section II, can only be apprehended through the actual realisations, in spacetime, which the *quantised fields* encode.

A natural question, if not a possible proviso to the above statement, could arise along the following reasoning. The spacetime manifolds of relativity theories are made of localised event-points. The sets of such points are reasonably assumed to be dense enough to justify a formal description in terms of *differentiable manifolds* endowed with appropriate topologies. Event-points are *geometric* objects for either the *Poincaré symmetry group* in the Minkowski case, or the group of *diffeomorphisms* of the spacetime manifold in the case of General Relativity.

But if our material Universe is generated out of its first quantum physical determinations shouldn't we rather think of a *quantum spacetime manifold* made out of *geometric* quantum event-points? One may observe that this would be the more sensical as, nowadays, *metrology*

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but they are not relativistically *invariant* [28] is precisely based on atomic physics.

It turns out that such a formal construction has effectively been achieved some years ago [29]. Physically, quantum points can be taken to be those of light pulses intersections. Relying on the *conformal symmetry* obeyed by massless fields' states, the quantum points can be associated to space and time quantum operators of localisation, and display properties endowing them with a genuine geometric character [11].

Now, whatever the interest of this quantum spacetime manifold in itself or for any other purposes, it must be realised that within the proposed understanding of the quantum reality, no change is brought to the statement that quantum fields *are not* in spacetime.

In effect, quantum points result from intersections of light pulses which are definitely finite energy measurable excitations of the photon quantum field. They can effectively give rise to geometric localisations for their light pulses intersections, but to no localisation at all for the photon quantum field itself.

Along this consideration, it is enlightening to recall how scientific philosophers have long thought of the notion of a field. J.-M. Levy-Leblond writes:

'The notion of field was born the last third of the 19th century. Already on the classical level, the notion of field requires the conception of a new mode of substantial existence, since we must renounce the idea of the necessary and natural primary qualities of matter in the sense of Descartes and Locke: A field has neither *extension*, nor solidity, nor figure, nor *mobility* to take up the Lockian list of these qualities [30]'.

Of course, the notion of field became even less intuitive when, some decades later, this same field acquired a quantised form, and became an 'operator-valued tempered distribution on a given representation space of states'. It is thus remarkable that beyond the involved mathematical apparatus of $QFTs$, the current understanding of the quantum physical reality which is being proposed is able to recover the fields' peculiarities just evoked [30].

By the way, the proposed understanding of the quantum reality does even more, rooting these peculiarities in the fact that elementary quantum fields as such being not in spacetime, neither extension nor mobility can be ascribed to them [4].

To sum up,

[11] Such a construction can be viewed as part of the attempts at unifying gravitation geometric theories with quantum field theories, by constructing a sound *quantum geometry*.

◇ Correlation functions are established within the framework of quantised fields, over any spacetime. This independence of quantised fields from spacetime points to a true exteriority to space and to time which are just labels on a given spacetime manifold which is taken to be as if it were there *already*, a non trivial epistemological position which could be considered elsewhere.

◇ However, as is well known, correlation functions in the fields involve explicit spacetime dependences, insofar as correlations are relative to finite energy *excitations* in the fields [24], which make for *propagations* that are inherently related to space and to time [4].

## IV. FROM THE CLOSURE OF BELL'S TYPE EXPERIMENTS LOOPHOLES

### A. Making a long story very short: The Bohr-Einstein debate

As is well known, Einstein was reluctant to the $QM$ probabilistic aspects, and took them as an indication that $QM$ was indeed an incomplete theory. Everyone knows his famous words 'God doesn't play dices!' [12]. This issue has been the matter of a long confrontation with Bohr whose intuitions didn't comply with Einstein's ideas. In 1935, with N. Rosen and B. Podolsky, Einstein conceived a genuine 'machine of war' against $QM$ [31] which was to become 'one of the most significant scientific contributions to $QM$ since its inception [32]'.

Recognising the internal consistency of the $EPR$ arguments, Bohr refused the conclusion the only way he could do it, that is by refuting the hypothesis on which the so-called '$EPR$ theorem' relied, usually regrouped under the name of *local realism.* There are several aspects of the $EPR$ arguments [32] which will not be recalled here in order to focus on one of them, tightly related to the notion of physical reality in its relations to spacetime, that is to the very core of the current analysis.

Bell's theorem, years later, in 1964, is a continuation of the $EPR$ argument and shows that in certain situations at least, $QM$ conflicts with the assumption of local realism the $EPR$ argument started from [33]. Now the interesting point is that this contradiction could be given the form of inequalities concerning measurable quantities; and that experimental tests could eventually be realised [32], which could not be envisaged in the times of $EPR$.

[12] To which sentence a physicist once replied by saying in a Conference 'Yes, God plays dices. Simply, He always wins!'

Soon after Bell's work, experimental tests began and quickly cumulated an impressive and convincing evidence that the $QM$ predictions are perfectly valid, including precisely the interesting cases where violations of Bell's type inequalities were recorded.

If no experiment can claim to be totally loop-hole free [34], be it by principle only, it is really remarkable that ten years ago the reliability of Bell's type experimental tests has been checked to a very high degree of accuracy [35], closing the door on a large variety of possible experimental loop-holes.

### B. Unescapable consequence

Not seeping into the numerous technical details and definitions at play, which have by now become textbook material [36], a *historical* Bell inequality, such as the $BCHSH$ inequality (Bell-Clauser-Horne-Shimony-Holt), would involve an expression like

$$C = A_0 B_0 + A_0 B_1 + A_1 B_0 - A_1 B_1 \tag{9}$$

where the $A_i$ and $B_j$, $i, j = 0, 1$, are four *hermitian* operators such that $[A_i, B_j] = 0$. They are associated to two couples of dichotomous observables, two observables for Alice and two for Bob, the experimenters, whose sole outcomes are conveniently normalised to $+1$ and $-1$. Then for any state $|\Psi >$ of the quantum system considered it is possible to prove that the following inequality holds,

$$|\langle\Psi|A_0 B_0 + A_0 B_1 + A_1 B_0 - A_1 B_1|\Psi\rangle| \leq 2\sqrt{2} \tag{10}$$

where the number $2\sqrt{2}$ is the *Cirelson bound* [36]. Would the local realism point of view be relevant to the quantum physical reality, then the upper bound would only be 2 instead of $2\sqrt{2}$, a clear-cut difference. In effect, re-writing (9) as $C = A_0(B_0 + B_1) + A_1(B_0 - B_1)$ one realises, within local realism, that $C$ can only take the values $\pm 2$, and thus for all normalised state $|\Psi\rangle$ one would find the so-called $BCHSH$ inequality,

$$|\langle\Psi|A_0(B_0 + B_1) + A_1(B_0 - B_1)|\Psi\rangle| \leq 2 \tag{11}$$

Now, a simple proof of (10) has the merit to discriminate quantum aspects from the classical aspects inherent to the local realism hypothesis. Taking $A_i^2 = B_j^2 = 1$ into account together with $[A_i, B_j] = 0$, $\forall i, j = 0, 1$, the expression of $C^2$ can be cast into the form,

$$C^2 = 4\mathbf{I} - [A_0, A_1][B_0, B_1] \tag{12}$$

where $\mathbf{I}$ is the identity matrix of format $2 \times 2$. In the classical case of vanishing commutators, one recovers the $BCHSH$ upper bound of 2, (11), while in the quantum case where *operator's norms* satisfy $||\,[A_0, A_1]\,|| \leq 2||A_0||\,||A_1|| \leq 2$, the Cirelson bound of $2\sqrt{2}$ follows immediately, (10).

The considerations above are but formal quantum mechanical translations of experimental setups realised with entangled pairs of spin 1/2 or spin 1 particles. In the latter case, when prepared as optimised pairs of photons *entangled in polarisation*, experimental tests carried on *singlet states* of total spin zero for convenience, can lead to measures of $|C|$ up to $2\sqrt{2}$. This is in accord with the $QM$'s prediction (10) and in obvious violation of the local realism hypothesis of (11). Even more striking violations can be obtained with three photons entangled in polarisation in so-called $GHZ$ states for which the $QM$ prediction, experimentally confirmed, gives a number of $+1$ when the local realism hypothesis leads to a number of $-1$ [37]. Indeed, violations of the local realism hypothesis is not restricted to the historical $BCHSH$ inequality only, but extends to several more Bell's type inequalities [13].

This astounding fact has received various denominations and expressions in the literature, like 'non-separability' or 'non-locality', or 'quantum correlations beat the Einstein causality', or 'quantum correlations leak out of the past and future relativistic cones of causality', which is equivalent to the previous one.

Here is the place where to let one of the World recognised expert conclude. In the paper 'Are There Quantum Effects Coming from Outside Spacetime?' N. Gisin writes [3]:

*If such correlations are observed, there is no choice but to admit that there are correlations that can't be explained by any story in space and time. Such correlations are thus said to be nonlocal: There is no 'local explanation', that is no explanation based on local causes that propagate from one place to adjacent ones.*

The connection to the currently proposed understanding of the quantum physical reality is clear. Whereas Bohr denied any quantum reality, the only physical reality being the classical one, according to a local realism point of view a quantum reality makes sense but

[13] B.S. Cirelson has been able to show that for any bipartite full-correlation Bell's type inequality with $m$ inputs for Alice and $n$ inputs for Bob, the ratio between the Cirelson bound and the local realism bound is at some *Gröthendieck constant* $K_G^{\mathbb{R}}(r)$ where $r = min\{m, n, -\frac{1}{2} + \sqrt{\frac{1}{4} + 2(m+n)}\}$. At $m = n = 2$, one recovers $K_G^{\mathbb{R}}(r) = \sqrt{2}$, [38].

is conceived a plainly actual one, deprived of any potential character.
The relation to spacetime is crucial here. In the view of local realism there is no exteriority and there is no exteriority either for Bohr, as this would be exteriority would exist in the physicists' minds only.
However, as keenly put forth by N. Gisin, quantum correlations are both plainly real and in no way reducible to any spacetime causation. Correlations 'communicate behind the scene', that is in a manner which does not depend on spacetime. This suggests the following:

- ◇ There is a physical reality exterior or 'before' spacetime
- ◇ Spacetime is 'after' quantum correlations

Another remark made by the same author [3] is useful to recall an important point already made in [6] that physics is local. It is noted that *Everything looks as if the two parties somehow communicate 'behind the scene' (...) Moreover it is not crystal clear that such communication behind the scene' would contradict relativity.*
And in effect, relativity is not contradicted [6]. There is no conflict at all with relativity because relativity applies to spacetime only, not to whatever 'happens' behind the spacetime scene.
The fact that there is a 'behind the scene' of spacetime accounts for this *elsewhere* one is looking for.

## V. WHAT *IS* THE 'BEHIND THE SCENE'

Quantum physics testifies to an elsewhere of spacetime, tightly related to its first and elementary physical determinations, the quantum fields that,

1- do not stand outside of the physical Universe,

2- are what the physical Universe is generated from [39],

3- are not themselves immersed in any Universe spacetime.

To resolve this difficulty, it is necessary to note that all the words used so far, which are commonly found in literature, refer to space or time. 'Before' and 'after' refer to time, 'outside', 'elsewhere', and 'enter' refer to space, and 'nonlocality' to space and time.
This is understandable, since we live in spacetime and because for centuries, physics has been built on the study of movements and measurements registered in spacetime.

However, such ways of expressing ourselves are doomed with circularity. While we try to construe what does not belong to spacetime, they confine us within spacetime. Continuing along this path, experience shows that words themselves become violently reluctant to such attempts and force thinking into paradoxical twists and turns with no real gains.

In order to catch what does not belong to spacetime,

1- an appropriate terminology must be used, which not only breaks with a spacetime terminology,

2- but complies also with the philosophical concepts which account for the behaviour of quantum objects in their relations to spacetime.

In fact, this situation is not unknown to quantum physics. For example, an essential property of elementary particles that always displays the same values regardless of the spacetime reference frame where it is measured is the spin of a particle. That is, it is not in spacetime until it is projected there by measurement. Spin, as a plain dimensional physical property, exists without being in spacetime in the first place. At the deepest level this is because spin is a property of the quantum field associated to the particle which is but a measurable finite energy excitation of the field. In the formal terms of *differential geometry* this translates into the fact that spin is not a *Lorentz-vector* of spacetime.

Thus, just as spin does not belong to spacetime *per se*, so too does what is 'behind the scene', which doesn't belong to spacetime 'before' it is actualised there.
Language is not without resources to express this peculiar situation. We speak of 'prior' or 'posterior' to express a relationship of order in a more general way. For example, cause and effect relate to each other according to prior and posterior, without necessarily including a reference to spacetime. Similarly, in classical physics, the existence of a mass is prior to all of its possible movements. The concept of an elementary particle is prior to the concept of a photon, and according to the order of logic, an axiom is prior to the properties that derive from it. Two of our previous assertions can accordingly be amended in the following manner:

◇ There is a physical reality prior to spacetime (instead of 'before').

◇ Spacetime is posterior to quantum correlations (instead of 'after').

Now, this effort of rigour in terminology is not a matter of linguistic accuracy only. It aims at complying with the fact that quantum realities evolve in a mode of existence that does not in itself relate to spacetime, but nonetheless encapsulates their relationships to spacetime, as formalisms testify in an explicit way. These are crucial points that emerge from analyses of Bell's type experiments, $QFTs$ and $QM$.

There is but one possible explanation for this situation, which is the anteriority of what is potential in relation to its actualisations. For a given material subject in effect, what is in a state of potency is prior to what is in act, according to 'the time of movement', such as conceived as the passage from potency to act [15].

- The quantum field is potential to its actualisations, and such is the anteriority observed in relation to measurements that are inherently inscribed in space and time.

- Similarly, in quantum mechanics, the reversibility of the unitary evolution of the wave-function is anterior to the arrow of time, because quantum realities stand in a state of potency with respect to their entry into spacetime, in particular by means of measurements. The $QM$ formalism is not deceptive which makes explicit that the unitary evolution is an evolution in the Hilbert space of the system states, not in spacetime itself.

- Elementary particles are plain quantum entities [4]. They do not have real and actual proper existences, aside from the experimental protocols which define them as such [40]. Strictly [41]. This is even more blatant with particles in entangled states. In a much deeper understanding therefore, the proper reality of elementary particles must be referred to that particular state of the quantum field associated to them [42]. It is it, this peculiar state of the field, which accounts for all of the subsequent measurements which, in a second step only, are described in terms of elementary particles in order to stick to the overall intuitive scheme that physicists have in mind and experiment [4, 23]. This peculiar quantum state, properly described by a wave-function in the case of Bell's type experiments, isn't in spacetime. A measure performed on it makes it enter spacetime in the manner of a collapse to which no *invariant* duration can be ascribed [6]. If this wave-function is that of an entangled pair of elementary particles, measures performed on one of either particles, and then on the other one, will necessarily manifest a perfect correlation of the results, irrespective of the spacetime distance separating the two measures. This is simply due to total angular momentum conservation. What makes such correlations appear to be the result of a 'spooky action at a distance' is that they (seem to) violate the Einstein causality, that is, *locality*.

[15] As long known, time as conceived within physical theories complies with this philosophical definition.

This is presumably what took A. Suarez to claim *'I argue that Einstein missed an important point: One cannot have conservation of energy without nonlocality at detection.'* [43], where 'conservation of energy' is here to be traded for 'total angular momentum conservation' in the case of Bell's type experiments.

This would really be an annoying situation because nonlocality is a negative notion that uncovers no thinkable physical reality. It should be clear on the contrary that the current paper argues that we are not condemned to this non-interpretation. Likewise, since no invariant duration can be ascribed to a collapse induced by a measuring process, no correlation speed can be defined either [6]. In this view, any attempt at explaining these correlations by introducing an extremely high correlation speed is not only doomed to failure [16] but makes no sense.

In full generality, classical physics included, relations to spacetime are determined by the relationships of given material potentialities to their respective acts. This philosophical understanding of the matter turns out to be both synthetic and universal because it applies to all of the various degrees of potentiality which quantum physics manifests.

Quantum potentialities in effect range from the maximal potentiality which is that of quantum fields [4] to the milder potentialities of *mesoscopic* objects like *SQUIDS* (Superconducting Quantum Interference Devices) involving up to $10^{10}$ electrons, or fullerene molecules $C_{70}$ comprising some 1300 elementary particles, and which still manifest quantum behaviours, though standing closer to ordinary bodies possessing their properties in an actual manner.

Beyond terminology, this philosophical explanation is rooted in the nature of the quantum realities, such as apprehended recently [4, 6]. This understanding seems to make sense of all of the quantum situations while letting any of them display their proper relations to space and time [6]. On the contrary, when this philosophical account is ignored, the fashionable interpretations of quantum physics in terms of nonlocality tend to come about and are likely to be nothing but non-interpretations, words with no definite physical content.

In order to account for the whole span of the quantum reality's 'crazy behaviours' in a rationale, in particular without appealing to *quantum angels* [44] who may be considered a

[16] Up to a speed limit of 50000 $c$, as mentioned in the Introduction, experience excludes any 'spooky action at a distance' [2].

revisited version of the older *sphere-pushing angels*, there seems to be no way around it.

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