Conditions for Lorentz-invariant superluminal information transfer without signaling

G Grössing[1], S Fussy[1], J Mesa Pascasio[1,2], H Schwabl[1],

[1] Austrian Institute for Nonlinear Studies, Akademiehof, Friedrichstr. 10, 1010 Vienna, Austria
[2] Atominstitut, TU Wien, Operng. 9, 1040 Vienna, Austria

E-mail: ains@chello.at

Abstract. We understand emergent quantum mechanics in the sense that quantum mechanics describes processes of physical emergence relating an assumed sub-quantum physics to macroscopic boundary conditions. The latter can be shown to entail top-down causation, in addition to usual bottom-up scenarios. With this example it is demonstrated that definitions of "realism" in the literature are simply too restrictive. A prevailing manner to define realism in quantum mechanics is in terms of pre-determination independent of the measurement. With our counter-example, which actually is ubiquitous in emergent, or self-organizing, systems, we argue for *realism without pre-determination*. We refer to earlier results of our group showing how the guiding equation of the de Broglie–Bohm interpretation can be derived from a theory with classical ingredients only. Essentially, this corresponds to a "quantum mechanics without wave functions" in ordinary 3-space, albeit with nonlocal correlations.

This, then, leads to the central question of how to deal with the nonlocality problem in a relativistic setting. We here show that a basic argument discussing the allegedly paradox time ordering of events in EPR-type two-particle experiments falls short of taking into account the contextuality of the experimental setup. Consequently, we then discuss under which circumstances (i.e. physical premises) superluminal information transfer (but not signaling) may be compatible with a Lorentz-invariant theory. Finally, we argue that the impossibility of superluminal signaling – despite the presence of superluminal information transfer – is not the result of some sort of conspiracy (á la "Nature likes to hide"), but the consequence of the impossibility to exactly reproduce in repeated experimental runs a state's preparation, or of the no-cloning theorem, respectively.

1. Emergent Quantum Mechanics: realism without pre-determination

The term "Emergent Quantum Mechanics" (EmQM) has been used in the literature for several years by now, albeit with different meanings regarding the word "emergence". As a major option, the term refers to the possibility that quantum theory might be a (very good) approximation to some "deeper level theory". To some, though, EmQM just stands for quantum theory as a special case for a particular set of parameters of a more encompassing theory. The term would thus refer to the *emergence of a theory*. However, the meaning of EmQM may also be more specific in that it refers to *physical emergence*, i.e., to the modeling of quantum systems as *emergent systems*. It is the latter option that our group has dealt with throughout the last couple of years.

There is, however, a communication problem in getting the relevant ideas across, mainly because the quantum physics and the self-organization/emergence communities, respectively, hardly communicate with each other. Specifically, the problem of accepting physical emergence as a possibility within the quantum physics community seems to be the rather exotic looking theme of *top-down causation* (next to bottom-up causation). Despite the fact that there are numerous examples in hydrodynamics, self-organizing systems, etc., for top-down causation, most quantum physicists seem unaffected by the possibility of this "unusual" type of causality, although the usual understanding of causality is apparently insufficient for a description and understanding of quantum processes. To give just one example, consider the Rayleigh–Bénard cells of hydrodynamics. There, one witnesses microscopic random movement that spontaneously becomes ordered on a macroscopic level. The top-down causality is manifest in that emergent particle trajectories depend crucially on the boundary conditions of the system.

Certainly, this classical example of top-down causation is neither "weird" (as quantum mechanics is claimed to be), nor "surreal" (as the trajectories' behaviors in the convection cells might be called, did one not have a perfectly rational explanation for it). Rather, this example must by necessity be covered by any definition of realism that one would claim as being generally applicable to any physical system. However, in the recent literature, definitions of realism have been proposed in the context of quantum foundations that would deny the above-mentioned examples of top-down causation to be considered "real". In other words, the phenomena of Rayleigh–Bénard cells in particular, but also all other processes of self-organizing, or emergent, systems, are actually counter-examples to recent definitions of "realism" in the quantum foundations literature, such as the following: "all measurement outcomes are determined by pre-existing properties of particles independent of the measurement (realism)." [1]

This is now to be contrasted with our proposal for a physical EmQM, i.e., *realism without pre-determination*. Instead of pre-determination, in the systems of interest we consider the case of co-evolution, i.e., permanently updated co-determination, with essential influences on the microphysics by changing boundary conditions, or measurement arrangements, respectively. With this perspective, it becomes clear that via importing ill-defined concepts of "realism" into the debate about Bell's theorems, all sorts of wrong conclusions become possible. After all, in this scenario "realism" effectively just becomes a "red herring", with the task of killing all proposals of thus understood "realistic" hidden variable theories – an exercise that in the end is rather fruitless. Looking back on the development of quantum foundations throughout the last decades, one actually may get the impression that this kind of strategy to exclude realism in this way has kept a lot of people busy. A historian of science might be well advised to consider a study on "A Brief History of Red Herrings", or the like – this might turn into quite a voluminous book.

To give just one more example of such a red herring, not of recent times, but of half a century ago, consider the following passage from Richard Feynman's famous description of electrons passing a double slit:

"We now make a few remarks on a suggestion that has sometimes been made to try to avoid the description we have given [i.e., of the double slit experiment with electrons]: 'Perhaps the electron has some kind of internal works – some inner variables – that we do not yet know about. Perhaps that is why we cannot predict what will happen. If we could look more closely at the electron, we could be able to tell where it would end up.' So far as we know, that is impossible. We would still be in difficulty. Suppose we were to assume that inside the electron there is some kind of machinery that determines where it is going to end up. That machine must also determine which hole it is going to go through on its way. But we must not forget that what is inside the electron should not be dependent on what *we* do, and in particular upon whether we open or close one of the holes.

So, if an electron, before it starts, has already made up its mind (a) which hole it is going to use, and (b) where it is going to land, we should find P_1 for those electrons that have chosen hole *1*, P_2 for those that have chosen *2*, and necessarily the sum $P_1 + P_2$ for those that arrive through the two holes. There seems to be no way around this. But we have verified experimentally that this is not the case. And no one has figured a way out of this puzzle. So at the present time we must limit ourselves to computing probabilities. We say 'at the present time,' but we suspect very strongly that it is something that will be with us forever – that it is impossible to beat that puzzle – that this is the way nature really *is*." [2]

It is interesting to see how strongly Feynman insists on his conclusion about "the way nature really *is*", although the logic his argument is based on depends on the unquestioned assumption that the electron's behavior is pre-determined, and independent of the measurement. This assumption, however, is in stark contrast to an alternative scenario which is proposed in our EmQM, i.e., that the electron does not propagate in a completely empty space, but is embedded in a "medium". The latter we identify as the vacuum's zero-point field, which can mediate information about the boundary conditions as given by the source and the measurement apparatus. The zero-point field is also the decisive agent in describing the electron's behavior in stochastic electrodynamics [3], with which our ansatz shares some characteristics, and a prototype to illustrate wave-particle duality via particle-medium interactions is given by the famous experiments with oil droplets "walking" on an oil bath [4–6].

So, there is one essential characteristic that radically contrasts particle behavior in our EmQM to that insinuated by above-quoted definition of "realistic" hidden variable theories: Instead of pre-determined velocities of the latter, the particles in our EmQM exhibit emergent velocities stemming from the constant interplay of the particle forward velocity at a particular instant in time with the wave-like embedding surroundings of the zero-point field. Said constant interplay, or mutual influencing, of particle and wave dynamics (which has its classical analogy in Couder's oil droplets, or "walkers"), is a manifestation of what we call *relational causality*: the interlocking of bottom-up and top-down causalities. Assuming local microscopic interactions in a sub-quantum domain, these form – together with the macroscopic boundary conditions – emergent structures in the quantum domain which may exhibit spontaneous nonlocal order. In turn, the thus created emergent structures affect the local microscopic interactions in a top-down manner, which thus closes the causal circle relating vastly different spatial scales at the same time (Fig. 1.1).

We have applied the concept of relational causality to the situation of double-slit interference (Fig. 1.2). Considering an incoming beam of, say, electrons with wave number $\mathbf{k}$ impinging on a wall with two slits, two beams with wave numbers $\mathbf{k}_A$ and $\mathbf{k}_B$, respectively, are created, which one may denote as "pre-determined" quantities, resulting also in pre-determined velocities $\mathbf{v}_I = \frac{1}{m}\hbar\mathbf{k}_I$, $I{=}A$ or B. The definition of "realism" (but also Feynman's dictum) that we criticized above would now imply that any realistic hidden variable theory just has these pre-determined velocities at its disposal for modeling double-slit interference. This, however, would constitute a very naive form of realism which, to our knowledge, nobody in the quantum physics community supports (... thus making it a classical red herring)!

However, if one considers that the electrons are not moving in empty space, but in an undulatory environment created by the ubiquitous zero-point field "filling" the whole experimental setup, a very different picture emerges. For then one has to combine all the velocities/momenta at a given point in space and time in order to compute the resulting, or "emergent", velocity/momentum field $\mathbf{v}_i = \frac{1}{m}\hbar\boldsymbol{\kappa}_i$, $i{=}1$ or 2 (Fig. 1.2), where i is a bookkeeping index not necessarily related to the particle coming from a particular slit [7]. The relevant contributions other than the particle's forward momentum $m\mathbf{v}$ originate from the so-called osmotic (or diffusive) momentum $m\mathbf{u}$. The latter is well known from Nelson's stochastic theory [8], but its identical form has been derived by one of us from an assumed sub-quantum nonequilibrium thermodynamics [9, 10]. Introducing the osmotic momentum in a sub-quantum hidden variable theory constitutes a decisively concrete step beyond the much older, but only rather general proposal by one of us of "quantum systems as 'order-out-of-chaos'

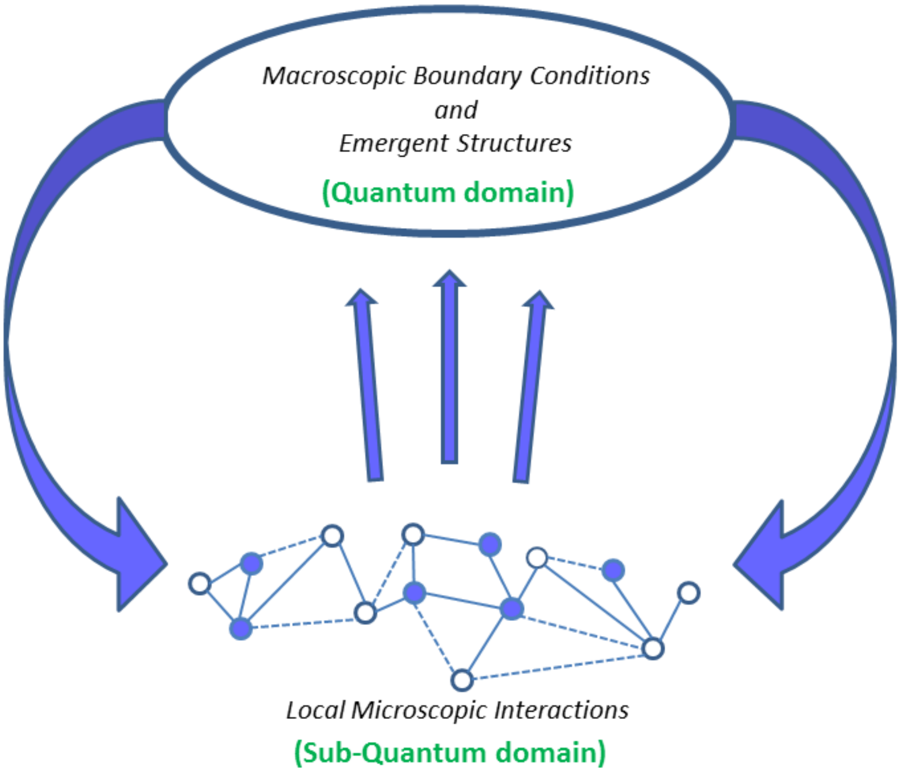

Figure 1.1. Scheme of relational causality: mutual (bottom-up and top-down) processes at the same time.

phenomena" [11]. For now it becomes possible to model double slit interference in more detail, with momentum conservation guaranteed as soon as one takes both the co-evolving forward and the osmotic velocity fields into account [7, 12]. This constitutes, among others, a viable causal model with its implied violation of what is called "causal parameter independence". The latter would state that in EPR-type scenarios Alice's measurement outcomes would not depend on Bob's measurement settings. However, as local changes of boundary conditions such as the settings of an apparatus nonlocally affect the whole system, our relationally causal model does describe said dependence and is therefore not excluded by recent no-go principles for certain causal hidden variable theories [13]. Not only that, our model also provides an understanding and deeper-level explanation of the microphysical, causal processes involved, i.e., of the "guiding law" [14], which also happens to be identical with the central postulate of the de Broglie–Bohm theory.

2. Identity of the emergent kinematics of N bouncers in real 3-dimensional space with the configuration-space version of de Broglie–Bohm theory for N particles

As in our model the "particle" is actually a bouncer in a fluctuating wave-like environment, i.e. analogously to the Couder's bouncers, one does have some (e.g. Gaussian) distribution, with its center following the Ehrenfest trajectory in the free case, but one also has a diffusion to the right and to the left of the mean path which is just due to that stochastic bouncing. Thus the total velocity field of our bouncer in its fluctuating environment is given by the sum of the forward velocity $\mathbf{v}$ and the respective diffusive (or "osmotic") velocities $\mathbf{u}_{\mathrm{L}}$ and $\mathbf{u}_{\mathrm{R}}$ to the left and the right. As for any direction α the diffusion velocity $\mathbf{u}_\alpha = D\frac{\nabla_\alpha P}{P}$, $\alpha = L$ or R, does not necessarily fall off with the distance, one has long effective tails of the distributions which

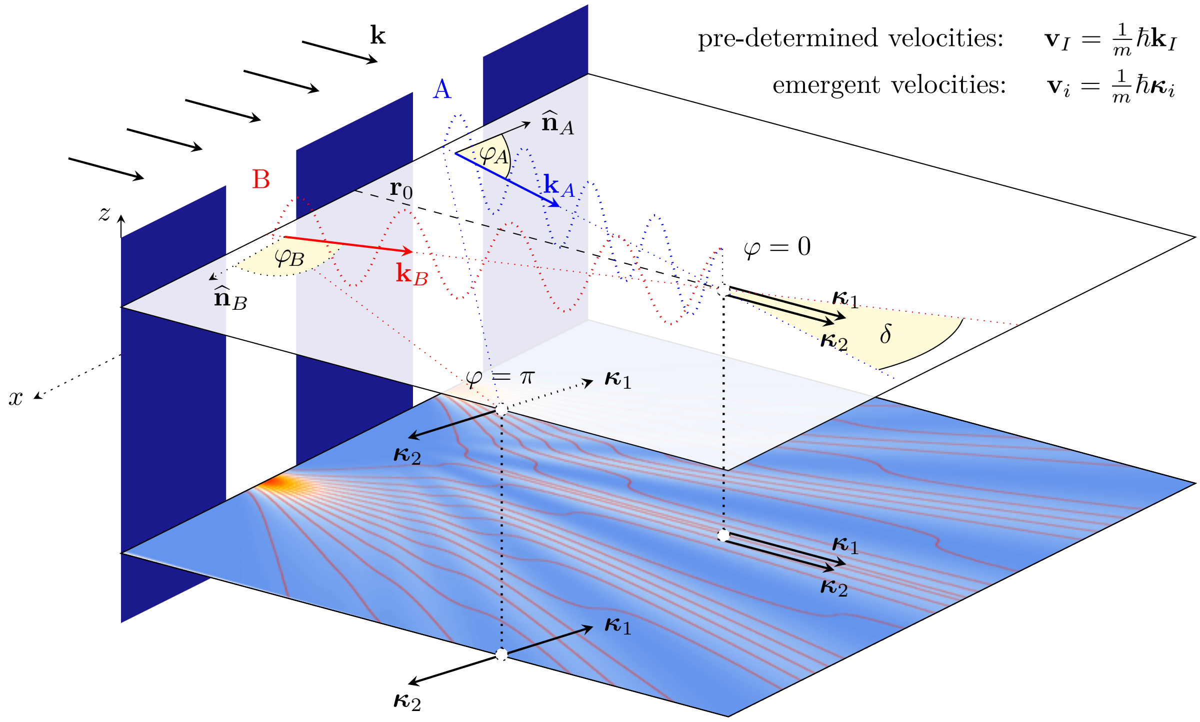

Figure 1.2. Scheme of interference at a double slit. Considering an incoming beam of electrons with wave number $\mathbf{k}$ impinging on a wall with two slits, two beams with wave numbers $\mathbf{k}_A$ and $\mathbf{k}_B$, respectively, are created, which one may denote as "pre-determined" quantities, resulting also in pre-determined velocities $\mathbf{v}_I = \frac{1}{m}\hbar\mathbf{k}_I$, $I{=}A$ or B. Recent definitions of "realism" in the quantum foundations literature would now imply that *any* realistic hidden variable theory just has these pre-determined velocities at its disposal for modeling double-slit interference. However, if one considers that the electrons are not moving in empty space, but in an undulatory environment created by the ubiquitous zero-point field "filling" the whole experimental setup, a very different picture emerges. For then one has to combine all the velocities/momenta at a given point in space and time in order to compute the resulting, or "emergent", velocity/momentum field $\mathbf{v}_i = \frac{1}{m}\hbar\boldsymbol{\kappa}_i$, $i = 1$ or 2. The relevant contributions differing from the particle's forward momentum $m\mathbf{v}$ originate from the so-called osmotic (or diffusive) momentum field $m\mathbf{u}$. Thus it becomes possible to model double slit interference in microscopic detail, as can be seen from the lower plane where intensity distributions and average trajectories are shown. Local momentum conservation is thereby guaranteed as soon as one takes both the co-evolving forward and the osmotic velocity fields into account.

contribute to the nonlocal nature of the interference phenomena [15]. In sum, one has three, distinct velocity (or current) channels per slit in an n-slit system.

We have previously shown [7,16] how one can derive the Bohmian guidance formula from our bouncer/walker model. Introducing classical wave amplitudes $R(\mathbf{w}_i)$ and generalized velocity field vectors $\mathbf{w}_i$, which stand for either a forward velocity $\mathbf{v}_i$ or a diffusive velocity $\mathbf{u}_i$ in the direction transversal to $\mathbf{v}_i$, we account for the phase-dependent amplitude contributions of the total system's wave field projected on one channel's amplitude $R(\mathbf{w}_i)$ at the point $(\mathbf{x}, t)$ in the following way: We define a *conditional probability density* $P(\mathbf{w}_i)$ as the local wave intensity $P(\mathbf{w}_i)$ in one channel (i.e. $\mathbf{w}_i$) upon the condition that the totality of the superposing waves is given by the "rest" of the $3n-1$ channels (recalling that there are 3 velocity channels per slit). The expression for $P(\mathbf{w}_i)$ represents conditions which we describe as "relational causality": any change in the local intensity affects the total field, and *vice versa*, any change in the total field affects the local one. In an n-slit system, we thus obtain for the conditional probability densities and the corresponding currents, respectively, i.e. for each channel component i,

$$P(\mathbf{w}_i) = R(\mathbf{w}_i)\widehat{\mathbf{w}}_i \cdot \sum_{j=1}^{3n} \widehat{\mathbf{w}}_j R(\mathbf{w}_j) \tag{2.1}$$

$$\mathbf{J}(\mathbf{w}_i) = \mathbf{w}_i P(\mathbf{w}_i), \qquad i = 1, \ldots, 3n, \tag{2.2}$$

with

$$\cos\varphi_{i,j} := \widehat{\mathbf{w}}_i \cdot \widehat{\mathbf{w}}_j. \tag{2.3}$$

Consequently, the total intensity and current of our field read as

$$P_{\mathrm{tot}} = \sum_{i=1}^{3n} P(\mathbf{w}_i) = \left(\sum_{i=1}^{3n} \widehat{\mathbf{w}}_i R(\mathbf{w}_i) \right)^2 \tag{2.4}$$

$$\mathbf{J}_{\mathrm{tot}} = \sum_{i=1}^{3n} \mathbf{J}(\mathbf{w}_i) = \sum_{i=1}^{3n} \mathbf{w}_i P(\mathbf{w}_i), \tag{2.5}$$

leading to the *emergent total velocity field*

$$\mathbf{v}_{\mathrm{tot}} = \frac{\mathbf{J}_{\mathrm{tot}}}{P_{\mathrm{tot}}} = \frac{\sum_{i=1}^{3n} \mathbf{w}_i P(\mathbf{w}_i)}{\sum_{i=1}^{3n} P(\mathbf{w}_i)}. \tag{2.6}$$

In [7, 16] we have shown with the example of $n = 2$, i.e. a double slit system, that Eq. (2.6) can equivalently be written in the form

$$\mathbf{v}_{\mathrm{tot}} = \frac{R_1^2 \mathbf{v}_1 + R_2^2 \mathbf{v}_2 + R_1 R_2 \left(\mathbf{v}_1 + \mathbf{v}_2\right) \cos\varphi + R_1 R_2 \left(\mathbf{u}_1 - \mathbf{u}_2\right) \sin\varphi}{R_1^2 + R_2^2 + 2R_1 R_2 \cos\varphi}. \tag{2.7}$$

The trajectories or streamlines, respectively, are obtained in the usual way by integration. As first shown in [17], by re-inserting the expressions for convective and diffusive velocities, respectively, i.e. $\mathbf{v}_i = \frac{\nabla S_i}{m}$, $\mathbf{u}_i = -\frac{\hbar}{m} \frac{\nabla R_i}{R_i}$, one immediately identifies Eq. (2.7) with the Bohmian guidance formula. Naturally, employing the Madelung transformation for each path j ($j = 1$ or 2),

$$\psi_j = R_j \mathrm{e}^{\mathrm{i} S_j/\hbar}, \tag{2.8}$$

and thus $P_j = R_j^2 = |\psi_j|^2 = \psi_j^* \psi_j$, with $\varphi = (S_1 - S_2)/\hbar$, and recalling the usual trigonometric identities such as $\cos\varphi = \frac{1}{2}\left(\mathrm{e}^{\mathrm{i}\varphi} + \mathrm{e}^{-\mathrm{i}\varphi}\right)$, one can rewrite the total average current immediately in the usual quantum mechanical form as

$$\begin{aligned}
\mathbf{J}_{\mathrm{tot}} &= P_{\mathrm{tot}} \mathbf{v}_{\mathrm{tot}} \\
&= (\psi_1 + \psi_2)^* (\psi_1 + \psi_2) \frac{1}{2} \left[\frac{1}{m} \left(-\mathrm{i}\hbar \frac{\nabla(\psi_1 + \psi_2)}{(\psi_1 + \psi_2)} \right) + \frac{1}{m} \left(\mathrm{i}\hbar \frac{\nabla(\psi_1 + \psi_2)^*}{(\psi_1 + \psi_2)^*} \right) \right] \\
&= -\frac{\mathrm{i}\hbar}{2m} \left[\Psi^* \nabla \Psi - \Psi \nabla \Psi^* \right] = \frac{1}{m} \mathrm{Re} \left\{ \Psi^* (-\mathrm{i}\hbar\nabla) \Psi \right\},
\end{aligned} \tag{2.9}$$

where $P_{\text{tot}} = |\psi_1 + \psi_2|^2 =: |\Psi|^2$.

Eq. (2.6) has been derived for one particle in an n-slit system. However, it is straightforward to extend this derivation to the many-particle case [14]. *Therefore, what looks like the necessity in the de Broglie–Bohm theory to superpose wave functions in configuration space, can equally be obtained by superpositions of all relational amplitude configurations of waves in real 3-dimensional space. The central ingredient for this to be possible is to consider the emergence of the velocity field from the interplay of the totality of all of the system's velocity channels.*

It can also be shown that the average force acting on a particle in our model is the same as the Bohmian quantum force. For, due to the identity of our emerging velocity field with the guidance formula, and because they essentially differ only via the notations due to different forms of bookkeeping, their respective time derivatives must also be identical. Thus, from Eq. (2.6) one obtains the particle acceleration field (using a one-particle scenario for simplicity) in an n-slit system as

$$\begin{aligned}
\mathbf{a}_{\text{tot}}(t) &= \frac{\mathrm{d}\mathbf{v}_{\text{tot}}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\sum_{i=1}^{3n}\mathbf{w}_i P(\mathbf{w}_i)}{\sum_{i=1}^{3n} P(\mathbf{w}_i)}\right) \\
&= \frac{1}{\left(\sum_{i=1}^{3n} P(\mathbf{w}_i)\right)^2}\Bigg\{\sum_{i=1}^{3n}\left[P(\mathbf{w}_i)\frac{\mathrm{d}\mathbf{w}_i}{\mathrm{d}t} + \mathbf{w}_i\frac{\mathrm{d}P(\mathbf{w}_i)}{\mathrm{d}t}\right]\left(\sum_{i=1}^{3n} P(\mathbf{w}_i)\right) \\
&\qquad - \left(\sum_{i=1}^{3n}\mathbf{w}_i P(\mathbf{w}_i)\right)\left(\sum_{i=1}^{3n}\frac{\mathrm{d}P(\mathbf{w}_i)}{\mathrm{d}t}\right)\Bigg\}.
\end{aligned} \tag{2.10}$$

Note in particular that (2.10) typically becomes infinite for regions $(\mathbf{x}, t)$ where $P_{\text{tot}} = \sum_{i=1}^{3n} P(\mathbf{w}_i) \to 0$, in accordance with the Bohmian picture.

From (2.10) we see that even the acceleration of one particle in an n-slit system is a highly complex affair, as it nonlocally depends on all other accelerations and temporal changes in the probability densities across the whole experimental setup! In other words, this force is truly emergent, resulting from a huge amount of bouncer-medium interactions, both locally and nonlocally. This now leads to the central question of how to deal with the nonlocality problem in a relativistic setting. We shall discuss this problem by considering EPR-type experiments.

3. Nonlocality and relativity: A case for Lorentz invariant superluminal information transfer

As is well known, in an EPR-type experiment, where two photons are emitted in opposite directions from one spin-zero state, two different observers would form mutually inconsistent pictures of reality (Fig. 3.1).

However, Maudlin has correctly pointed out that "Relativity also reveals some of the apparent contradictions between frames to be merely matters of equivocation." [18] He explains: "The unprimed (here: l.h.s.) frame says that the right-hand photon is detected before the left while the primed (here: r.h.s.) frame has it the other way around. How could they both be right? In this case the answer is clear: they are simply talking about different things. The unprimed

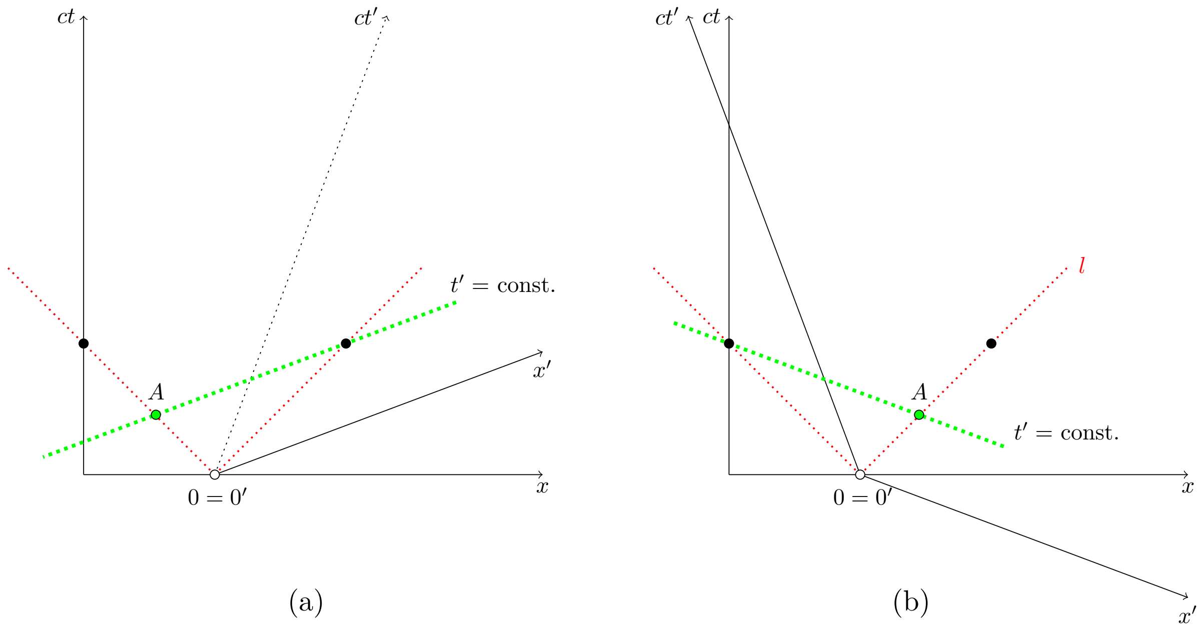

Figure 3.1. (a) An EPR-correlated particle pair is emitted at source *0* and later simultaneously registered by detectors (symbolized by black circles) in the laboratory rest frame. However, an observer in a reference frame moving to the right, would see the right-hand particle registered at a time *t'* at which the left-hand particle is located at spacetime point A. Thus, a "state jump" would occur at A before the particle is registered. (b) Same as in (a), but with observer in a reference frame moving to the left. The latter will see the left-hand particle registered at time *t'* at which the right-hand particle is located at spacetime point A, so that a "state jump" would occur at A before the particle is registered. Taken together, (a) and (b) point at a conflict as to which order of events "really" is happening in a realistic world view.

frame notes precedence in its t-coordinate, which we might call 'time', while the primed frame is concerned with precedence in its own t-coordinate, which we could call 'primetime'. There is no more contradiction between saying that the right detection event precedes the left in time but follows it in primetime than there is in saying that Idaho precedes New Jersey in geographical area but follows it in terms of population." [18]

So, the riddle posed in Fig. 3.1 is solved by realizing that there does not exist the one "true time ordering". All that matters is the Lorentz invariance of the theory. Paraphrasing Maudlin, we add "space" and "primespace" in the scenario, just to obtain frames of "spacetime" and "prime-spacetime". Then, our two different viewpoints are two versions of a Lorentz invariant behavior in space and time, which can be transformed into each other via simple rotation, as required by the Lorentz transformations (Fig. 3.2).

Again, we agree with Maudlin as to the consequences of this insight. He argues that many would agree that "Relativity prohibits something from going faster than light:

Matter or energy cannot be transported faster than light.

Signals cannot be sent faster than light.

Causal processes cannot propagate faster than light.

Information cannot be transmitted faster than light."

But, alternatively, one just needs to require that theories must be Lorentz invariant: "This requirement is compatible with the violation of every one of the prohibitions listed above." [18] However, in order to clearly see the implications of the required Lorentz invariance, one must appreciate that the whole experimental arrangement has to be taken into account, i.e., including

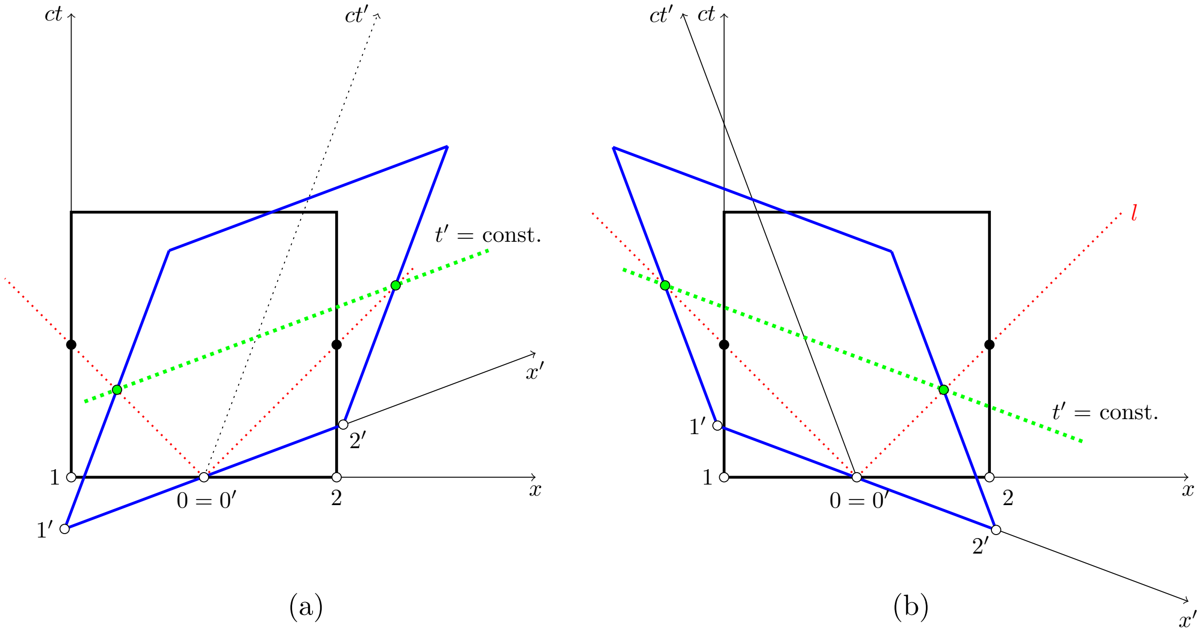

Figure 3.2. As Lorentz transformations correspond to simple rotations in spacetime diagrams, the two situations of Fig. 3.1 just correspond to two different viewpoints. However, what is crucially important to be able to show this, is that one has to take into account the whole experimental arrangement including the source *0* and the detectors *1* and *2*, in each reference frame. Then, even nonlocal correlations (symbolized by the green line) are part of a relativistically invariant description. Moreover, this renders obsolete the question of which of the options (a) and (b) was the "true" time ordering.

the source *0* and the detectors *1* and *2*, in each reference frame. Then, even nonlocal correlations (symbolized by the green line in Fig. 3.2) are part of a relativistically invariant description.

An especially interesting scenario is given for the case that the two frames meet such that the spacetime points at the origin coincide, i.e. *1=1'* (Fig. 3.3). In the resting laboratory frame, the experiment is arranged along an area between points *1* and *2*, with the source *0* emitting photon pairs at time $t_0 \geq 0$. Imagine now that to each element of the experimental setup is attached a traffic light that shows "red" when the preparation is not yet completed, and "green" when it is. In the rest frame, the totality of all traffic lights showing "green" will occur at some first instance, i.e., at some time $t_0 = \text{const}$. Now, what would a moving observer see? The answer is given by Rindler's "wave of simultaneity": whereas the green lights will light up in a "flash" which in the rest frame occurs simultaneously at the time $t_0 = 0$, in the moving observer's frame they will light up simultaneously at some time $t_0^{'} = 0$. (For a more detailed description, with arguments involving a "rigged Hilbert space", see [19].) This has the strict consequence that the photon pairs can be emitted from source *0'* only at times $t_0^{'} \geq 0$. And this is also the source of misleading arguments in the literature. For, although the lightcone is defined uniquely in all reference frames, this is true only as to its spreading in spacetime due to the universality of the vacuum speed of light. However, the *timing* of the emission of the photon pairs must in general be different for two observers moving with relative velocities to each other. In other words, one has to consider the relativity of simultaneity of the whole experimental setup including the source and the extension of the apparatus. Note also that if the moving observer would register at A a photon that was emitted at *0*, we would have the same kind of dilemma as in Figs. 3.1 (a) and (b). For then the "state jump" of the left-hand photon would occur at $\underline{A}$, i.e., before its arrival at the detector $\underline{B}$. However, if one correctly describes the source *0'* of the particle

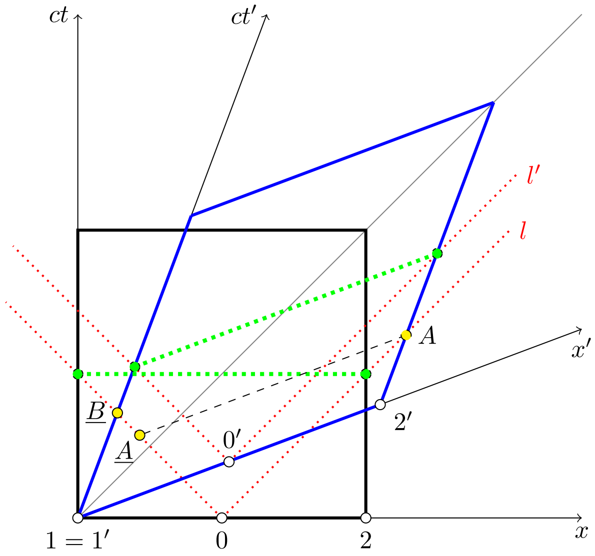

Figure 3.3. In the laboratory rest frame, the EPR-correlated particle pair is emitted at source *0* and later simultaneously registered by detectors (symbolized by green circles). If, under the wrong assumption, the moving observer would register at A a photon that was emitted at *0*, then the "state jump" of the left-hand photon would occur at $\underline{A}$, i.e., before its arrival at the detector at $\underline{B}$. However, since the preparation of an entangled photon pair requires the preparation of the whole experimental setup, and not just of the source, the world lines of all elements of the apparatus must be considered as forming one unseparable whole. Therefore, the photon pairs can be emitted from source 0' only at times $t_0^{'} \geq 0$. Consequently, also in the moving frame will the photons arrive simultaneously at the respective detectors, and Lorentz invariance is again established.

pair in the moving observer's rest frame, then the detectors at points *1'* and *2'*, respectively, would always simultaneously register the corresponding photons. Thus, by relating the axis of equitemporality to the whole extension of an experimental apparatus in spacetime, which is different for each reference frame, one avoids the error of attributing some "idealistic" time to the system (like, e.g., $t' = \text{const}$ in Figs. 3.1 (a) and (b)).

We have thus shown that even nonlocal correlations can be part of a relativistically invariant description of events in spacetime. The conditions for Lorentz-invariant superluminal information transfer are essentially given by the evolution in spacetime of the whole, encompassing system (i.e., quantum system plus macroscopic apparatus, including source and detectors). A crucial question then arises as to interventions in such a system, which lead to the phenomenon of *dynamical nonlocality* [20]. In the above-mentioned paper by one of us [11], a type of experiment called "late choice experiment" was proposed that we then believed would provide an effect with dramatic consequences. The question was clarified for us only fairly recently in the paper by Tollaksen *et al.* [20], with the consequence that although the effect exists its measurable consequences are not dramatic at all. We shall here only refer to the variant that Tollaksen *et al.* discuss, for it is the relevant one. Essentially, the authors ask what happens in a realistic scenario (where one electron goes through just one of two slits present) if at the very moment the particle passes the slit, the other slit is being closed (or opened, in case it was closed before). The authors show within the Heisenberg picture that the opening or closing of a slit results in the nonlocal transfer of (what they call "modular") momentum. (Our group has shown that this effect can also be demonstrated when using the Schrödinger picture [15].)

However, there is an in-principle uncontrollability of that momentum transfer: Tollaksen *et al.* [20] speak of "complete uncertainty" in this regard. This means that here one has the case of a nonlocal transfer of information (i.e., from a slit to the particle), which, however, cannot be used for signaling: due to the necessary uncertainty of the location of the particle before the intervention, the nonlocal momentum transfer just shifts the particle within the wave packet, figuratively speaking, so that its detection at some location cannot in principle give any indication of whether or not that information transfer has happened.

A corollary to this concerns an implication of the no-cloning theorem. Opening or closing of a slit amounts to the preparation of a new state with a certain phase relative to the one associated with the path of the particle through the other slit. Considering many runs with such an intervention highlights an important feature of the system: it cannot be controlled. In other words, the identical phase can *never* be reproduced, which means that the no-cloning theorem is here ultimately responsible for the impossibility of superluminal signaling. (For, if one could control the phase during intervention at a slit, one could do this massively in parallel, and thus on average steer the electron to a desired position.)

Thus, both the consistencies of relativity and of quantum theory are confirmed, despite the superluminal information transfer involved. In other words, complete uncertainty makes it possible to have *nonlocal information transfer without superluminal signaling*. The latter is exactly the option shown in [21] to remain valid for viable nonlocal hidden variable theories.

Acknowledgments
We thank Jan Walleczek for many enlightening discussions, and the Fetzer Franklin Fund of the John E. Fetzer Memorial Trust for partial support of the current work.

References

[1] Gröblacher S, Paterek T, Kaltenbaek R, Brukner C, Zukowski M, Aspelmeyer M and Zeilinger A 2007 An experimental test of non-local realism *Nature* **446** 871–875 (*Preprint* arXiv:0704.2529 [quant-ph])
[2] Feynman R P, Leighton R B and Sands M 1966 *The Feynman Lectures on Physics: Quantum Mechanics* vol 3 (Addison-Wesley)
[3] de la Peña L, Cetto A M and Valdés-Hernándes A 2014 *The Emerging Quantum: The Physics behind Quantum Mechanics* (Berlin: Springer) ISBN 978-3-319-07893-9
[4] Couder Y, Protière S, Fort E and Boudaoud A 2005 Dynamical phenomena: Walking and orbiting droplets *Nature* **437** 208–208
[5] Bush J W 2015 Pilot-wave hydrodynamics *Annu. Rev. Fluid Mech.* **47**(1) 269–292
[6] Batelaan H, Jones E, Huang W C W and Bach R 2016 this volume
[7] Fussy S, Mesa Pascasio J, Schwabl H and Grössing G 2014 Born's rule as signature of a superclassical current algebra *Ann. Phys.* **343** 200–214 (*Preprint* arXiv:1308.5924 [quant-ph])
[8] Nelson E 1966 Derivation of the Schrödinger equation from Newtonian mechanics *Phys. Rev.* **150**(4) 1079–1085
[9] Grössing G 2008 The vacuum fluctuation theorem: Exact Schrödinger equation via nonequilibrium thermodynamics *Phys. Lett.* A **372**(25) 4556–4563 (*Preprint* arXiv:0711.4954 [quant-ph])
[10] Grössing G 2009 On the thermodynamic origin of the quantum potential *Physica* A **388** 811–823 (*Preprint* arXiv:0808.3539 [quant-ph])
[11] Grössing G 1989 Quantum systems as «order out of chaos» phenomena *Nuov. Cim.* B **103**(5) 497–509
[12] Grössing G, Fussy S, Mesa Pascasio J and Schwabl H 2010 Emergence and collapse of quantum mechanical superposition: Orthogonality of reversible dynamics and irreversible diffusion *Physica* A **389**(21) 4473–4484 (*Preprint* arXiv:1004.4596 [quant-ph])
[13] Ringbauer M, Giarmatzi C, Chaves R, Costa F, White A G and Fedrizzi A 2016 Experimental test of nonlocal causality (*Preprint* arXiv:1602.02767 [quant-ph])
[14] Grössing G, Fussy S, Mesa Pascasio J and Schwabl H 2015 Implications of a deeper level explanation of the deBroglie–Bohm version of quantum mechanics *Quantum Stud.: Math. Found.* **2**(1) 133–140 (*Preprint* arXiv:1412.8349 [quant-ph])
[15] Grössing G, Fussy S, Mesa Pascasio J and Schwabl H 2013 'Systemic nonlocality' from changing constraints on sub-quantum kinematics *J. Phys.: Conf. Ser.* **442** 012012 (*Preprint* arXiv:1303.2867 [quant-ph])

[16] Grössing G, Fussy S, Mesa Pascasio J and Schwabl H 2014 Relational causality and classical probability: Grounding quantum phenomenology in a superclassical theory *J. Phys.: Conf. Ser.* **504** 012006 (*Preprint* arXiv:1403.3295 [quant-ph])

[17] Grössing G, Fussy S, Mesa Pascasio J and Schwabl H 2012 An explanation of interference effects in the double slit experiment: Classical trajectories plus ballistic diffusion caused by zero-point fluctuations *Ann. Phys.* **327**(2) 421–437 (*Preprint* arXiv:1106.5994 [quant-ph])

[18] Maudlin T 2011 *Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics* 3rd ed (West Sussex, UK: Wiley-Blackwell) ISBN 978-1-4443-9697-3

[19] Grössing G 2000 *Quantum Cybernetics: Toward a Unification of Relativity and Quantum Theory via Circularly Causal Modeling* (New York, NY: Springer) ISBN 978-0-387-98960-0

[20] Tollaksen J, Aharonov Y, Casher A, Kaufherr T and Nussinov S 2010 Quantum interference experiments, modular variables and weak measurements *New J. Phys.* **12**(1) 013023 (*Preprint* arXiv:0910.4227v1 [quant-ph])

[21] Walleczek J and Grössing G 2016 Nonlocal quantum information transfer without superluminal signalling and communication *Found. Phys.* In press. (*Preprint* arXiv:1501.07177 [quant-ph])