# Duration and its Relationship to the Structure of Space-Time

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**Abstract**

**The notion of duration is a fundamental feature of intuitive time. Under the assumption that the duration of a measurement is defined to produce a result with certainty, we define a universal observer who observes the position of a physical system. We investigate what conclusions for the structure of space-time the universal observer can draw. It turns out that the perspective of this observer is compatible with the Minkowski structure of space-time.**

**Key Words: Quantum Physics, Special Relativity, Measurement, Galilean space-time, Entropy**

## 1. 1 troductio. 1

Non-relativistic quantum physics is formulated in Galilean space-time and, accordingly, the intuitions behind the notion of time are drawn from the structure of a Galilean world. Galilean space-time admits a universal time parameter and a foliation into space-like simultaneity hyper-surfaces, which define a universal time-order. In addition every process takes some period of time $\Delta t$, its duration, and this duration stays the same, if the identical process is repeated. These are two fundamental aspects of time and in Galilean space-time both are independent of the location or uniform movement of a clock[1] measuring them. This is different in Minkowski space-time, which is the result of the empirical fact that the speed of light, $c$, is invariant under boosts, i.e. independent of the velocity of a light-source [1]. In Minkowski space-time it is impossible to define simultaneity, and even future and past outside of the light-cone, independently of the movement of a clock. Duration on the other hand can still be invariantly defined via the notion of "eigentime" $s$. However, $s$ is not universal anymore. A lot of work has been done on the topic of simultaneity, which is a bone of contention between the presentist and the eternalist world-view [2]. While relativity theory clearly favors the eternalist view, the by now experimentally well-established quantum non-separability is hard to reconcile with it [3]. H. Poincaré says in an essay [4] that the simultaneity of events and the equality of duration might be mere conventions. As mentioned, most focus has since been laid on the question of simultaneity, while duration has seemed to be less problematic. We think differently and will show that, while quantum physics enforces a discussion around simultaneity, it also enforces one around duration, which has profound consequences and even helps to clarify the first discussion.

## 1. 1o. 1r. tr tiuistic1qur . tum1physics1

Non-relativistic quantum physics is formulated in Galilean space-time, but the laws governing the dynamics of matter are distinctly different to Newton's laws or their

[1] We do not enter into the question what kind of device a clock really is.

relativistic extensions. There is a complex-valued function $\varphi(x,t)$, called wave function, which assigns to a matter-entity[2] the probability to be in a specific space-volume $dx$ around an event $(t,x)$ in space-time

$$p(dx,t) := \varphi(x,t) \cdot \varphi^*(x,t)dx = |\ \varphi(x,t)\ |^2\ dx, \tag{1}$$

$$\int_{\mathbb{R}^3} |\varphi(x,t)|^2 dx = 1 \cdot$$

The dynamics happens in two different ways. There is an evolution of the wave function, governed by the Schrödinger equation

$$\begin{gathered} i\hbar \frac{\partial}{\partial t} \varphi(x,t) = H\varphi(x,t) \\ \varphi(x,0) = \varphi_0. \end{gathered} \tag{2}$$

$H$ denotes a positive semi-definite operator (Hamiltonian) on the space of wave functions. This equation determines the evolution of the probability density (1). The wave function does not live in space-time but in an abstract function-space and its arguments reside in a high-dimensional configuration space, only different from physical space though, if two or more matter-entities are in scope. The probability densities (1) are covariant under Galilean-boosts, $x \to x - vt, t \to t$, and hence Galilean space-time is consistent with the theory of matter so far.

Any interaction of a matter-entity, represented by φ, with another matter-entity is described by a Schrödinger equation. This holds in particular for an interaction with a measurement apparatus $A$. Assume there is an apparatus $A$, which is also described by a vector in some abstract space, having a pointer-basis $\{A_0, A_x\}$ with $A_0$ denoting "no position measurement done" and $A_x$ corresponding to "the matter-entity detected at point $x$". There is some interaction Hamiltonian $H_A$ such that we can formalize the measurement process in the spirit of (2) by

$$\varphi_0 \otimes A_0 \overset{H_A}{\to} \sum_x \varphi_0\,(x)\delta_x \otimes A_x. \tag{3}$$

Equation (3) leaves the matter-apparatus system in a non-definite superposition of mutually orthogonal states. This is not what we observe and it is here, where the second kind of dynamics enters the stage, namely the collapse. Traditional quantum physics postulates that at some point in the process there is a discontinuous collapse, which reduces the matter-apparatus system to a distinct state $\delta_x A_x\rangle := \delta_x \otimes A_x$.

The theory of matter outlined so far describes the random appearance of matter-entities caused by measurements in physical space at time $t$. It does not say anything about what matter does "in between" measurements, since the evolution of the wave function does not live in physical space but in an abstract function space. Of course, the theory also says something about the measurement of physical properties other

[2] We use the term "matter-entity" for matter without specification of an ontology.

than position.[3] Since we are interested in the structure of space and time, the other property of interest is momentum. Values of physical properties are eigenvalues of self-adjoint operators, which act on the wave-function $\varphi$. The position-operators are the multiplication-operators $X_i(\varphi) \coloneqq x_i \cdot \varphi, 1 \leq i \leq 3,$ and the spectrum consists of the elements $x \in \mathbb{R}$. The momentum-operators turn out to be $P_i(\varphi) \coloneqq -i\hbar \frac{d}{dx_i}\varphi, 1 \leq i \leq 3$, with the same spectrum. The corresponding values are empirically found by measurements. We note, that the universal time parameter $t$ is not on equal footing with position or momentum, since there is no operator, which could account for it, as there cannot exist a self-adjoint time-operator that is canonically conjugate to a Hamiltonian having a semi-bounded spectrum [5].

The traditional interpretation (Copenhagen) assumes the apparatus $A$ to be a macroscopic system. In our context it might be any system with which a matter-entity interacts, as long as the interaction results in a measurement (3) [6]. We have so far not specified a matter-ontology and used the term "matter-entity" for a system represented by a wave function $\varphi$. Quantum theory is general enough to support different ontologies. We can think of matter-entities being particles, like in classical physics.[4] The wave function, however, also lends itself to an ontology where a matter-entity is somehow "smeared" out as a matter-density in the whole of space and gets localized by measurement [7]. Just assume there is an experiment with two detectors at two different, spatially separated wings. Before the measurement there is matter density on both wings but as soon as the detector on either of the wings fires (i.e. the state collapses), there is nothing on the other side anymore. At the moment of firing there is a kind of instantaneous influence between the two wings. This is an example of non-separability, which has been tested in various experiments with two or more entangled matter-entities [8,9,10]. It cannot be explained by common causes, localized in the past, nor can it be used to send signals [3, *chap.* 4]. What it does, however, is to naturally define a simultaneity hyper-surface. Hence Galilean space-time with its unique foliation into simultaneity hyper-surfaces is a good structure to harbor the collapse of an entangled system. At the same time the existence of these hyper-surfaces is hard to reconcile with relativity [3].

Differently to the situation in classical physics, we also know that a measurement does not only discover already existing values of physical properties but does in a way create them by the context of the measurement [11]. The role of the observer $(A, H_A)$is hence crucial in quantum physics. In the same spirit not all physical properties can together be exactly measured, which is also a marked difference to a classical theory of matter. Particularly position and momentum form an incommensurable pair of properties. This is the content of another defining postulate of quantum physics, namely the canonical commutator-relation.[5] There holds for the position and momentum operators $x_i$ and $-i\hbar\frac{d}{dx_j}, 1 \leq i,j \leq 3,$[6]

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[3] By physical properties we understand properties, which assume numerical values by measurement.
[4] This ontology was developed by L. de Broglie and D. Bohm by adding further structure to quantum physics.
[5] Note that the representation of the momentum-operator in x-space is a consequence of the canonical commutator relationship and vice versa.
[6] For a pair of self-adjoint operators $A, B$ the commutator is $[A, B] \coloneqq AB - BA$.

$$\left[x_i, -i\hbar\frac{d}{dx_j}\right] = i\hbar\delta_{ij}. \tag{4}$$

So far we have seen that we can think of physical reality in Galilean space-time as being a set of measurement outcomes lying on simultaneity slices $S_t$ at different times $t$. Galilean space-time allows us now to look into the past and into the future and to think of reality at different (absolute) times. How are these slices connected? It is not possible to think of (expectation) values of matter-entities as a flow in space-time. The violation of the Leggett-Garg inequalities [12] either demands that at time $t$ there might be no value at all and/or that a measurement changes the future development. There is no flow if "nobody looks". What we realize by this is that different observers might give different accounts of the world. Consistency ensures that, if they interact at some time $t_0$, then they agree on the immediate findings [6]. Measurement has another consequence. By reducing information available before measurement it seems to run counter to the second law. A way to balance the entropy account is to agree that a measurement induces a corresponding dissipation of entropy to the environment [13,14]. This mechanism will be important later.

Let us now assume that at time $t_0$ an observer starts a number of position-measurements on a set of independent (i.e. non-interacting) matter-entities. We know that at some time in the future the observer will find a position for each of them. But when will this be the case? Equation (3) just says that within some time $\Delta t = \bar{t}$ an individual apparatus-matter system will develop like

$$\Psi_0 := \varphi_0 \otimes A_0 \longrightarrow \sum_x \varphi_0\,(x)\delta_x \otimes A_x := \Psi_{\bar{t}}, \tag{5}$$

and

$$\langle \Psi_0 | \Psi_{\bar{t}} \rangle = 0.$$

Let us follow [15] and define a self-adjoint operator $M_X$ on the matter-apparatus system by

$$M_X \coloneqq \sum_x \delta_x A_x\rangle\langle\delta_x A_x. \tag{6}$$

The operator $M_X$ has two eigenvalues $\lambda \in \{0,1\}$, 1 denoting "measurement completed" and 0 standing for "measurement incomplete," i.e.

$$M_X(\delta_x \otimes A_y) = \delta_{xy} \cdot (\delta_x \otimes A_y).$$

Therefore, at any time $0 \le t \le \bar{t}$, the expression

$$P(t) \coloneqq \langle \Psi_t | M_X | \Psi_t \rangle$$

represents the probability for the measurement to be completed. By construction there holds $P(\bar{t}) = 1$. So there is, right in the spirit of quantum physics, a probabilistic answer to the question "after what period of time is the position measurement complete". The probability $P(t)$ does not resolve the conundrum what actually happens at a measurement. What it does, is to indicate to an observer with what probability there is a result after an interval $\Delta t \subset [0, \bar{t}]$. [7] Under this regime the observer at $t_0$ cannot know which of the matter-entities will have[8] a position prior to, later than or simultaneous with the others. The future has no predictable time-order and it is difficult to define a notion of duration at all, since the observer could repeat the procedure and for each trial get different time-intervals. Could we compress the time $\bar{t}$ to an arbitrarily small interval? A theorem by N. Margolus and L. Levitin shows that this is only possible under condition of a correspondingly large initial energy $[16]$. For a Schrödinger evolution (2) the minimal time $\tau$, until $\varphi_0$ reaches an orthogonal state $\varphi(\tau)$ is bounded below by

$$\tau \geq \frac{h}{4(\bar{E} - E_0)} \tag{7}$$

with

$$\bar{E} = \langle \varphi_0 | H_A | \varphi_0 \rangle.$$

$E_0$ denotes the lowest eigenvalue of $H_A$. The probabilistic nature of occurrence in time is perfectly aligned with the general probabilistic nature of quantum physics as a theory of matter. In order to define clocks, however, one has to ensure that a second "today" is a second "tomorrow" and hence to respect the minimal time interval $\tau$. If we demand in the sequel that a measurement (5) produces a result with certainty, we will talk of "occurrence-certainty" and mean that it takes time $\Delta t = \bar{t}$ such that $P(\bar{t}) = 1$. There is a practical impossibility by (7) to compress the period until occurrence-certainty is reached to an arbitrarily small interval.

Non-relativistic quantum physics is formulated on the background of Galilean space-time and eo ipso the momentum operator is unbounded. The lack of trajectories does not allow the definition of a classical velocity for a single system.[9] It can however be defined on the level of expectation values and then appears for instance as the group velocity of a wave-packet. Still, we find in every single experiment that no quantum system, prepared at one position in space, can be detected at another position in a period shorter than it would take it to move there at the speed of light and the speed of light is independent of the velocity of its source. If quantum physics is the fundamental theory of matter, then we should be able to explain these facts in terms of the theory. Relativity is a classical theory but the findings of the experiments above evidently do not only hold for macroscopic matter-entities. Because of its crucial importance in quantum physics, they might then hinge on the appropriate definition of an observer who asks the right question.

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[7] Note that the time-span $\Delta t$ calculated in (5) is a relational quantitiy in the sense of $[20]$, whereas the time-point $t$ of collapse is not and rather qualifies as a gauge-quantity.

[8] We cannot go into the subtle question, whether a matter-entitiy actually has a position or is just found to be somewhere relative to the observer.

[9] The velocities, defined by the additional structure of the de Broglie Bohm theory, are also unbounded.

## 3. 3. e universal observer

Our general discussion above indicates that in non-relativistic quantum physics a measurement cannot happen within an arbitrarily short period of time, if it should produce a result with certainty. By (7) a measurement takes a minimal amount of time $\tau$, defined by

$$\tau \geq \frac{h}{4(\bar{E} - E_0)}. \quad (8)$$

As tacitly assumed all the time, what's been measured is position in space. The average energy $\bar{E}$ depends upon a matter-entity with wave function $\varphi_0$ and the interaction Hamiltonian $H_A$ with an apparatus $A$, leaving $\tau(\varphi_0, H_A)$ very case-dependent.

Let us introduce a universal observer, namely the environment $\Xi$, with an average (equilibrium) temperature $T$, in which the matter-entity and the apparatus are embedded. As indicated before, each measurement lowers the (von Neumann) entropy $S_{\varphi_0}$ of the reduced matter-apparatus system to zero and must therefore trigger an increase of entropy in the environment of (at least) the same amount. This mechanism can be explained by the erasure of a former apparatus-state [13,14]. As a result there is dissipation of an average amount of energy

$$\bar{E} = k_B T S_{\varphi_0} \quad (9)$$

into the environment, where $k_B$ denotes the Boltzmann constant [14].[10] For the average energy of the dissipation Hamiltonian of the total system, $H_\Xi \otimes \mathbb{I}_{A\otimes\varphi}$, we have, with $\xi_0$ denoting the initial environment-sate,

$$\bar{E} = \langle \xi_0 | H_\Xi | \xi_0 \rangle \cdot \langle \delta_x A_x | \delta_x A_x \rangle = k_B T S_{\varphi_0}.$$

Let us denote the density matrix of the reduced matter-apparatus system by $\Psi_{\varphi_0}$. There holds for the von Neumann-entropy

$$S_{\varphi_0} = -tr\left(\Psi_{\varphi_0} log_2(\Psi_{\varphi_0})\right).$$

In other words the flow of the Hamiltonian $H_\Xi \otimes \mathbb{I}_{A\otimes\varphi}$ on the total system generates the same time-scale as the Hamiltonian $H_{\Psi_{\varphi_0}} = -k_B T log_2(\Psi_{\varphi_0})$ does on the reduced matter-apparatus system.[11] Let us denote by $\Lambda_0^{\Psi_{\varphi_0}}$ the lowest eigenvalue of $-log_2(\Psi_{\varphi_0})$. By (7) the environment state $\xi_0$ moves into an orthogonal state $\xi_1$ in an amount of time $\tau$

$$\tau \geq \frac{h}{4k_B T(S_{\varphi_0} - \Lambda_0^{\Psi_{\varphi_0}})}. \quad (10)$$

[10] In the present context the temperature $T$ is best being thought of as the average energy per bit of information, defined by $k_B T = \frac{\partial \bar{E}}{\partial s}$.

[11] This is a link to the concept of thermal time [21].

Ultimately, the fact that the matter-apparatus system is in some position-state $\delta_x A_x\rangle$ is reflected in the thermal degrees of the environment and it takes at least the time-amount $\tau$ in (10) until the environment, i.e. the universal observer, has unambiguously noticed this fact.

Let $\varphi$ denote a matter-entity, which is isotropically emitted at the origin, i.e. only depends on the distance r from the origin.[12] We will work for simplicity reason in one space-dimension. Given an interval $[0, R]$, $R \in \mathbb{R}^+$, we denote by $\mathbb{P}_R$ the multiplication with the characteristic function $\mathbb{I}_{[0,R]}$ and by $\mathbb{P}_R^\perp$ the one with $\mathbb{I}_{[R,\infty)}$. There is an orthogonal decomposition of $\varphi$ into

$$\varphi = \mathbb{P}_R\varphi + \mathbb{P}_R^\perp\varphi = \varphi_R + \varphi_R^\perp.$$

These projectors represent a self-adjoint operator standing for the question whether the matter-entity is within the range $[0, R]$ or not. The corresponding density matrix is

$$\Phi_R = \begin{pmatrix} \int_0^\infty |\varphi_R|^2 dr & 0 \\ 0 & \int_0^\infty |\varphi_R^\perp|^2 dr \end{pmatrix}. \tag{11}$$

For the entropy $S_{\Phi_R}$ we have

$$S_{\Phi_R} = -\left[\left(\int_0^R |\varphi|^2 dr\right) log_2\left(\int_0^R |\varphi|^2 dr\right) + \left(\int_R^\infty |\varphi|^2 dr\right) log_2\left(\int_R^\infty |\varphi|^2 dr\right)\right]$$

$$\coloneqq G\left(\int_0^R |\varphi|^2 dr\right). \tag{12}$$

In addition

$$\Lambda_0^{\Phi_R} = \min\left\{-log_2\left(\int_0^\infty |\varphi_R|^2 dr\right), -log_2\left(\int_0^\infty |\varphi_R^\perp|^2 dr\right)\right\}.$$

Let us further assume that $\varphi$ is a Gaussian wave-packet with mean wave number $\langle k\rangle = k$ and variance $\sigma_k^2$

$$\varphi(r) = \sqrt{\frac{2\sigma_k}{\sqrt{\pi}}}\, exp\left(-\frac{\sigma_k}{2} r^2\right) exp(ikr). \tag{13}$$

[12] In particular there is no angular-momentum.

If a detector is able to detect $\varphi$ within the interval $[0, R]$, then, if it is detected at all, its maximum range is $R$. By (10) it takes a minimal amount of time

$$\tau = \frac{h}{4k_B T(S_{\Phi_R} - \Lambda_0^{\Phi_R})}$$

for the measurement to be complete. Therefore we can define for $x \leq R$ a classical average velocity $v_\varphi$ and get the estimate

$$v_\varphi := \frac{\Delta x}{\Delta t} \leq \frac{\Delta R}{\tau} \leq \frac{4k_B T}{h}(S_{\Phi_R} - \Lambda_0^{\Phi_R}) \cdot R. \tag{14}$$

To estimate the right side of (14) we introduce the error function

$$\mathrm{erf}(r) := \frac{2}{\sqrt{\pi}} \int_0^r e^{-t^2} dt \cdot \tag{15}$$

We write with (12)

$$(S_{\phi_R} - \Lambda_0^{\Phi_R}) \cdot R = \frac{1}{\sigma_k}\left(G\big(erf(\sigma_k R)\big) - \Lambda_0^{\mathrm{erf}\,(\sigma_k R)}\right) \cdot (\sigma_k R) := \frac{1}{\sigma_k} H(\sigma_k R).$$

There holds $\lim_{R\to 0} H(\sigma_k R) = \lim_{R\to\infty} H(\sigma_k R) = 0$ [13] and, since the parameter $\sigma_k$ only appears in the argument, the maximum $C_0$ of $H$ over $[0, \infty)$ exists and is independent of $\sigma_k$.[14] We therefore get

$$v_\varphi \leq \frac{4k_B T}{h} \frac{C_0}{\sigma_k}. \tag{16}$$

We make use of the de Broglie relation $p = hk$ and write $h\sigma_k = \sigma_p$ to get

$$v_\varphi \leq \frac{4C_0}{\sigma_p} k_B T. \tag{17}$$

The expression $(S_{\Phi_R} - \Lambda_0^{\Phi_R}) \cdot R$ covariant and hence $C_0$ invariant under Galilean-boosts, since substitution in (12) will leave the volume-element invariant $d\bar{r} = dr$.

We now want to show that a refinement of $(17)$ generates indeed an estimate, which is consistent with empirical findings. Assume that the environment is filled with (blackbody) radiation. In the classical limit, $h\nu \ll k_B T$, the average energy of an oscillator with mode $\nu$ is indeed $\bar{E}_\nu \approx k_B T$, as used in $(17)$. More generally we get with Planck's second radiation law

[13] This can be seen e.g. from de l'Hôpital's rule.
[14] A calculation shows that $C_0 \approx 0.54$.

$$\bar{E}_\nu = \frac{h\nu}{2} + \frac{h\nu}{exp\left({}^{h\nu}/_{k_B T}\right) - 1}. \quad (18)$$

The modes with $h\nu \ll k_B T$ are excited with certainty whereas the higher energies have small probabilities and therefore (9) is a good lower approximation to the dissipated average energy $S_{\Phi_R} k_B T \lesssim \bar{E}$. For a given $\sigma_p$ there is a frequency $\nu_0$ such that

$$\sigma_p \geq \frac{h\nu_0}{c}. \quad (19)$$

If the temperature $T$ is small enough, we have $\bar{E} \leq S_{\Phi_R} \bar{E}_{\nu_0}$ and hence

$$v_\varphi \leq \frac{4C_0}{\sigma_p} \bar{E}_{\nu_0}. \quad (20)$$

Assuming in the final step that the environment is a vacuum by letting $T \to 0$, where a free particle in form of a Gaussian wave packet $\varphi$ can realistically exist, there finally results from (18), (19) and (20)

$$v_\varphi \leq 2C_0 c. \quad (21)$$

The right hand side of $(21)$ is indeed invariant under Galilean-boosts.[15]

We have shown that, if we let a radiating environment act as a universal observer in the sense that it notices with certainty that a position has been measured, then it is possible to define an average velocity of free, massive $(m > 0)$ particles and to find a boost-invariant upper bound for this velocity in vacuum. If the universal observer did physics, it would be able to derive the Minkowski structure of space-time. The question is, whether there is more evidence for Minkowski space-time, hidden in quantum physics. Indeed, we find further evidence, if we come back to the canonical commutator-relation $(4)$. The canonical commutator-relation symbolizes in point of fact the time $t$ $-$limit of the difference of two measurements, done in reverse order, one a little earlier at $t_-$ and the other a little later at $t_+$

$$\left[x_i, -i\hbar \frac{d}{dx_j}\right] \varphi(t) := \quad (22)$$
$$\lim_{t_\pm \to t} \left[ i\hbar \frac{d}{dx_j} \left(x_i \varphi(t_-)\right)(t_+) - x_i \left( i\hbar \frac{d}{dx_j} \left(\varphi(t_-)\right)(t_+) \right) \right].$$

In light of the above, the time delta of two definite outcomes $\Delta(t_+ - t_-)$ can no longer be made arbitrarily small without either increasing the probability that no measurement is completed at all or the assumption of an arbitrarily large interaction-energy. The commutator-relation (4) appears under the assumption of occurrence-certainty as a high energy-limit.

[15] $2C_0 c \approx 1{,}08 \cdot c$.

## 4. 4. canonical commutator4r lation

As was shown already in [17] and also in [18,19], the commutator-relation (4) indeed represents the $c \gg v$ –limit of the brackets of the Poincaré-algebra and not the ones of the Galilean-algebra. Denote by $T_0$ the generator of time-translations, $T_i, 1 \leq i \leq 3$, the generators of spatial translations and $K_i, 1 \leq i \leq 3$, the boost-generators in the Poincaré-algebra. We outline the derivation following [19]. There holds

$$[T_i, K_j] = -\left(\frac{i}{c^2}\right)\delta_{ij}T_0. \tag{23}$$

The commutator (23) vanishes in the Galilean-algebra where boosts and space-translations commute. There further holds, with $M$ denoting the mass operator $m \cdot \mathbb{I}, m \in \mathbb{R}$, and $P$ the four-impulse,

$$c^{-2}\hbar T_0 = (M + c^{-2}P^2)^{\frac{1}{2}} = M + \frac{P^2}{2Mc} + O(c^{-4}).$$

Together with

$$c^{-2}P_0 = c^{-2}\hbar T_0,$$

we arrive in the $c \gg v$- limit at

$$T_0 = \frac{c^2}{\hbar}M.$$

Defining now the impulse and position operators via $P_i = \hbar T_i$ and $Q_j = -\left(\frac{\hbar}{m}\right)K_j$, we derive (4)

$$[P_i, Q_j] = -\left(\frac{\hbar^2}{m}\right)[T_i, K_j] = -\left(\frac{\hbar^2}{m}\right)\left(\frac{i}{\hbar}\right)\delta_{ij}. \tag{24}$$

The transformations of space-time in this limit are the weakly-relativistic transformations, which for $\vec{v} = (v_x 0,0)$ take the form

$$x' = x - v_x t, t' = t - \frac{v_x x}{c^2}. \tag{25}$$

These transformations describe a world where there is no time-dilation nor-length contraction, but where simultaneity becomes gauge-dependent, if simultaneity is defined by synchronizing clocks using signals at speed c. Within some bounded region $\Omega$ of space $c \gg v$ implies that in $(25)$ $t \sim t'$. Non-relativistic quantum physics has, by postulating the commutator-relation (4) and thereby tacitly assuming occurrence-certainty and simultaneous measurement, all the time been living in a $c \gg v$-limit of a Minkowski world with potentially very large, but finite speed $c$. This fact went unnoticed, since the transformations (25) lead to a phase factor for wave functions consistent with the one under which the Schrödinger equation is shown to be Galilean invariant [19]. In addition within $\Omega$ the gauge dependence of simultaneity would practically be non-noticeable.

## 5. 5. nclusi. ns5

We have seen, that from the perspective of the universal observer it is possible to derive an invariant upper limit for the appropriately defined speed of free matter-entities in vacuum. This is the key to derive the Minkowski-structure of space-time, which in turn leads to the canonical commutator-relation (4) as a consequence of the Poincaré-algebra, i.e. the non-commutability of space and time-translations. In addition $\Delta(t_+ - t_-) \ll 1$ implies the space-time transformations $(25)$, where invariant simultaneity-surfaces approximately exists in a bounded region $\Omega$. Galilean space-time with its global simultaneity surfaces is then just the limiting case $c \to \infty$.

A key feature of the universal observer was occurrence-certainty. If probabilistic duration is allowed, then, because of the potentially arbitrarily small time period until a measurement result is realized, a kind of suddenness or collapse-like event is automatically part of the intuition. From $P(t) < 1$ it does not follow though, that the coming-into-being is instantaneous. Therefore the collapse postulate is truly independent of the duration-question and has the status of an additional axiom. It supports a Galilean structure of space-time.

As discussed, equation (7) can be viewed as the definition of a clock, which flips orthogonal states with corresponding period $\tau$. In paragraph 3 we chose a specific clock, namely light (electromagnetic radiation), in order to measure time intervals. The derivation of estimate (21) through the universal observer shows that the relativistic theory of space-time is naturally connected to the measurement of position and time by means of electromagnetism, which mirrors the original intension to combine electromagnetism and mechanics. The results also help to illuminate the discussion around different choices of clocks [22,23].

If Minkowski space-time is a realistic model for the world, then there remains the task to formulate quantum physics in a Lorentz-covariant form. Surely, the same conclusions as drawn in this paper will apply to the extended theory. If collapse is built in, then covariance will fail. What can also be said, given what we know, is that the notion of covariant position at some point in time $t$ must be problematic, since there can be no instantaneous position-measurement anymore. Concrete extensions indeed encounter this challenge, as is well known from quantum field theory. By the same token we can ask what happens, if the mechanism of a universal electromagnetic clock is applied to accelerated observers.

List of References


1. Michelson A.A., Morley E.W.: On the Relative Motion of the Earth and the Luminiferous Ether. American Journal of Science 34, 333-345 (1887)
2. Esfeld M.: Quantum physics and presentism. in Re-thinking time at the interface of physics and philosophy. The forgotten present. Cham: Springer, 231-248 (2015)
3. Maudlin, T.: Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics. Oxford: Basil Blackwell, Third Edition (2011)

4. Poincaré J.H.: La mesure du temps, Rev. Métaphys. 6 (1), (1898)
5. Hilgevoord J.: Time in quantum mechanics. American Journal of Physics 70(3), 301-306 (2002)
6. Rovelli C.: Relational Quantum Mechanics. Int. J. Th. Phys. 35, 1637 (1996)
7. Bedingham D., Dürr D., Ghirardi G., Goldstein S., Tumulka R., Zanghì, N.: Matter density and relativistic models of wave function collapse. Journal of Statistical Physics 154, 623–631 (2014)
8. Bell J.S.: On the Problem of Hidden Variables in Quantum Mechanics. Reviews of Modern Physics 38, 447-452 (1966)
9. Aspect A., Grangier P., Roger G.: Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities. Phys. Rev. Lett. 49(2), 91-94 (1982)
10. Tittel W., Brendel J., Zbinden H., Gisin N.: Violation of Bell inequalities by photons more than 10 km apart. Phys. Rev. Lett. 81, 3563 (1998)
11. Kochen S., Specker E.: The Problem of Hidden Variables in Quantum Mechanics. Journal of Mathematics and Mechanics 17, 59-87 (1967)
12. Leggett A.J., Garg A.: Quantum Mechanics versus macroscopic realism: is the flux there when nobody looks? Phys. Rev. Lett. 54, 857 (1985)
13. Lubkin E.: Keeping the entropy of measurement: Szilard revisited. Int. J. Th. Phys. 26(6), 523-535, (1987)
14. Plenio M.B., Vitelli V.: The physics of forgetting: Landauer's erasure principle and information theory. Contemp. Phys. 42, 25 (2001)
15. Rovelli C.: Incerto tempore, incertisque loci: Can we compute the exact time at which a quantum measurement happens? Found. Phys. 28(7), 1031-43 (1998)
16. Margolus N., Levitin L.B.: The maximum speed of dynamical evolution. Physica D 120, 188-195 (1998)
17. Kaiser G.: Phase-space approach to relativistic quantum mechanics. III. Quantization, relativity, localization and gauge freedom. J. Math. Phys. 22, 705-714 (1981)
18. Bohr A., Ulfbeck O.: Genuine Fortuitousness. Where Did That Click Come From? Found. Phys. 28(7), 757-774 (2001)
19. Stuckey W.M., Silberstein M., Cifone M.: Deflating Quantum Mysteries via the Relational Blockworld. Physics Essays 19, 269-283 (2006)
20. Rovelli C.: Why gauge? Found. Phys. 44(1), 91-104 (2014)
21. Connes A., Rovelli C.: Von Neumann algebra automorphisms and time thermodynamics relation in general covariant quantum theories. Quant. Class. Grav. 11, 2899-2918 (1994)
22. Borghi C.: Physical Time and thermal Clocks. Found. Phys. 46, 1374-1379 (2016)
23. Schlatter A.: A Brief Note on the Clock-Hypothesis. Journal of Modern Physics, 7, 2098-2102, (2016)