

Quantum Time

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Abstract. A short introduction, with extended interpretations, to the Projection Evolution approach is presented. In this model time is like the other space positions represented by an operator in the state space of a physical system. As a pedagogical example the Minkowski spacetime is considered. Finally, a short analysis of the time reversal symmetry is presented.

1. Introduction

In general, classical relativity treats time on the same footing as the other position variables. However, in quantum mechanics time still is considered as a kind of a parameter which allows the observer to divide the reality into past, present, and future, all three connected by the appropriate causality relations. There were many attempts to construct the time operator. However, limitations based on the Pauli theorem [1, 2] forced to construct these operators in a rather unnatural way in the single particle space $L^1(R^3, d^3x)$ instead of $L^1(R^4, d^4x)$ where the scalar product, which determines physical probability amplitudes, is defined as an integral over all four spacetime coordinates.

The work by E.A. Galapon showed that the Pauli's theorem can be overcome using weaker assumptions about the observables [3].

In this talk we propose a more natural approach in which time is a part of the spacetime position observable. The proposed idea is based on the paper (see also preprint) [4]. In this paper and preprint one can find extended but obviously limited set of references to papers on the time notion.

One may ask if time and space positions behave in the same way in the macroscopic and microscopic scales? To some extent the answer is hidden in the Bell's inequalities. The experiments [5, 6] show that (CHSH) type of Bell's inequalities

$$S = \langle A_a B_b \rangle - \langle A_a B_{b'} \rangle + \langle A_{a'} B_b \rangle + \langle A_{a'} B_{b'} \rangle, \quad (1)$$

where A, B represent some binary events, are broken in quantum world. For classical world the parameter $|S|$ should be smaller than 2, however, the observed value is $|S| > 2$, i.e., our world is quantal.

A few years ago the Bell's theorem was extended to the time domain [7].

The authors considered a thought experiment in which a massive body is in a spatial superposition. They show that it leads to entanglement of temporal orders between time-like



events. They conclude that the temporal order cannot be described by any pre-defined local variable and a classical notion of causality is therefore untenable in any framework quantizing classical general relativity.

One needs to notice that the Bell's theorem for temporal order wasn't checked experimentally, one can expect, however, similar result of such experiment as for the standard Bell's inequality because there are many other experiments which strongly suggest quantum nature of time. We shortly list a few of them which are often considered as quantum paradoxes.

One group of experiments is a series of the so-called delayed choice phenomena analyzed by J.A. Wheeler more than 40 years ago. The main idea of the "delayed choice" is the following: a system starts evolution at time t_0 and evolves in its own way. However, after changing some evolution conditions at time $t > t_0$ it "comes back to beginning of its evolution, forgetting what happened till time t " and it evolves in a way compatible with this new conditions, even though for an external observer it is an acausal event.

The simplest form of these phenomena are related to the well known double-slit experiments [8, 9]. They can be explained in a very natural way considering time as a quantum observable [11, 10].

A more sophisticated form of these experiments is known as the double-slit experiment with quantum eraser [12]. The effect was visible even when the changes introduced to the experimental setup led to acausal events.

Next type of time structure related experiments is based on quantum entanglement. Quantum entanglement and teleportation allow to construct correlated spacelike events [13, 14]. In this experiment the entangled pairs of photons were separated by 144 km. Even though the particles were causally disconnected (the signal 90 times faster than speed of light c was required to connect causally both particles) the changes made in the first laboratory were affecting the second particle.

There exists also a temporal version of entanglement, i.e., entanglement over the time dimension. In this case the experiment allowed to entangle two particles which existed in different time intervals [19]

If time in the quantum regime is treated as a quantum observable all physical objects states have to have some width in the time direction. This implies that every phenomenon is characterized not only by its duration time but also it evolves parallelly through different time intervals. It means that it should be possible to observe the temporal interference of quantum objects because of their spread in time. Time interference for particles passing time slits has been observed for different quantum systems [16, 17, 18].

In this short introduction we have chosen only a few phenomena which support the idea of quantum time as a quantum observable which should be considered on the same footing as the other quantum observables. It means that spacetime position has to be represented either by a four-component operator or an appropriate positive operator measure (POVM).

2. Projection evolution

Adding time to the set of quantum observables characterizing a quantum system requires adding it to its configuration space. In this case time becomes an additional physical degree of freedom of this object.

This observation excludes time to be an evolution parameter. We suggest that, in fact, spacetime is created as one of the properties of our Universe.

2.1. Changes principle

As a primary process in the Universe we assume its spontaneous changes and we postulate them as the basic law which we call **the changes principle**:

The evolution of a system is a random process caused by the spontaneous changes of quantum states in the Universe.

The Projection Evolution approach (PEv) is described in the paper [4], however, we add here some additional interpretations.

To apply the changes principle one needs to introduce a parameter τ which labels the subsequent steps of the projection evolution caused by the spontaneous changes of quantum states in the Universe. It is obviously not time.

The parameter τ has to belong to an ordered set. In principle, no other properties are required, however, on the actual level of the PEv development we assume, in addition, that every τ has a successor and one can enumerate changes using integers.

Theoretically it is possible to enumerate by τ all changes in the Universe. In practice it is a completely unrealistic task. Even considering any subsystem of the Universe we have to limit ourselves only to a subset of all available states representing changes/phenomena of this system and label them by $\tau_0, \tau_1, \tau_2, \dots$. Models are usually simplified in two ways: (i) not all degrees of freedom, phenomena and interactions are taken into account, (ii) not all intermediate steps of the system evolution are included in the model. The last statement requires additional explanation. It is clear, that between subsequent steps of the evolution labelled by τ_n and τ_{n+1} , a set of intermediate steps of the evolution can exist, which effectively leads from the initial states τ_n to the final states τ_{n+1} . Adding these additional steps one improves the “resolution” of the more primitive model. The existence of the best resolution model which includes all possible intermediate changes between the evolution steps τ_n and τ_{n+1} is an open problem.

All phenomena belonging to a given evolution step of a physical system, have to be related to measurable states of this system. For example, for quantum processes which start from an initial state $|\psi_i\rangle$ and pass through a set of intermediate interfering states $|\phi_k\rangle$ to a final state $|\psi_f\rangle$, the transition amplitude between such two states is given by $\langle\psi_f|\hat{P}_\phi|\psi_i\rangle$, where the operator \hat{P}_ϕ projects onto the subspace spanned by the intermediate states $|\phi_k\rangle$. These intermediate states cannot be considered as evolution steps.

2.2. Evolution operators

The next step of the projection evolution approach is the construction of the evolution operators which describe a set of allowed states in the subsequent step of the evolution.

The projection evolution operators at the evolution step τ_n , which transform from the evolution step τ_{n-1} to τ_n , are defined as a family of transformations:

$$\mathbb{F}(\tau_n; \nu_n, \cdot) : \mathcal{T}_1^+(\mathcal{K}(\tau_{n-1})) \rightarrow \mathcal{T}^+(\mathcal{K}(\tau_n)), \quad (2)$$

where $\mathcal{T}_1^+(\mathcal{K}(\tau_{n-1}))$ is the space of normalized quantum states at the evolution step τ_{n-1} , and $\mathcal{T}^+(\mathcal{K}(\tau_n))$ denotes the quantum state space at the evolution step τ_n . The pairs $(\tau_k; \nu_k)$, where ν_k are appropriate quantum numbers, determine quantum states at the evolution step τ_k uniquely.

The operators \mathbb{F} can be written in the form of the so-called Krauss operators:

$$\mathbb{F}(\tau_n; \nu_n, \rho) = \sum_{\alpha} \mathbb{E}(\tau_n; \nu_n, \alpha) \rho \mathbb{E}(\tau_n; \nu_n, \alpha)^\dagger, \quad (3)$$

where the summation over α is dependent on the quantum numbers ν_n and chooses some evolution channels required to get a state described by the set of quantum numbers ν_n .

In the standard quantum mechanics there are two evolution laws: (i) a unitary evolution, when a subsystem states are changing in a unique way, and (ii) a measurement (stochastic process) when one wants to determine some properties of the system. These two types of the evolution lead to a series of the so-called quantum paradoxes.

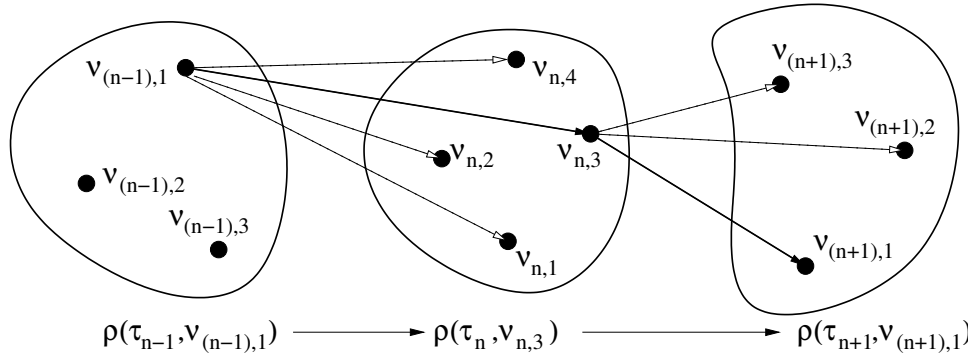


Figure 1. The density matrix ρ is randomly chosen at each evolution step τ from the possible states labeled by $\mathcal{Q}_m = \{\nu_{m,1}, \nu_{m,2}, \dots\}$, where $m = n - 1, n, n + 1$.

In case of the projection evolution we have only one evolution law. We propose the generalized Lüders projection postulate as the basic principle for the quantum evolution (the corresponding formula we call the chooser):

$$\rho(\tau_n; \nu_n) = \frac{\mathbb{F}(\tau_n; \nu_n, \rho(\tau_{n-1}; \nu_{n-1}))}{\text{Tr}(\mathbb{F}(\tau_n; \nu_n, \rho(\tau_{n-1}; \nu_{n-1})))}. \tag{4}$$

This set of the evolution operators provides a set of possible states $\rho(\tau_n; \nu_n)$ to which the system can evolve from the state $\rho(\tau_{n-1}; \nu_{n-1})$. As it was mentioned above the projection evolution is a stochastic process. It means, one needs to have formulae for the transition probabilities $\text{pev}(\rho(\tau_{n-1}; \nu_{n-1}) \rightarrow \rho(\tau_n; \nu_n))$ from the initial states $\rho(\tau_{n-1}; \nu_{n-1})$ to the final states $\rho(\tau_n; \nu_n)$.

The probability distribution for the chooser is given by **the quantum mechanical transition probability** from the previous to the next state. For pure states, for which $\rho(\tau_{n-1}; \nu_{n-1}) = |\psi(\tau_{n-1}; \nu_{n-1})\rangle\langle\psi(\tau_{n-1}; \nu_{n-1})|$ and $\rho(\tau_n; \nu_n) = |\psi(\tau_n; \nu_n)\rangle\langle\psi(\tau_n; \nu_n)|$ the transition probability is given by the well known expression $\text{pev}(\rho(\tau_{n-1}; \nu_{n-1}) \rightarrow \rho(\tau_n; \nu_n)) = |\langle\psi(\tau_n; \nu_n)|\psi(\tau_{n-1}; \nu_{n-1})\rangle|^2$. For mixed states these probabilities require deeper analysis.

In Figure 1. a schematic evolution process has been shown.

2.3. Evolution generators

In the standard approach to quantum mechanics the main object describing a quantum system is its Hamiltonian. Similarly, it turns out, that for many quantum systems one can construct the so-called projection evolution generator or a set of the evolution generators, eventually with some constraints, $\hat{\mathbb{W}}_k(\tau)$ which facilitate construction of appropriate evolution operators \mathbb{E}_k . They give also a link between traditional equations of motion and the evolution operators.

For a given evolution step τ , the projection evolution generator $\hat{\mathbb{W}}(\tau)$ is defined as a self-adjoint operator which spectral decomposition gives the orthogonal resolution of unity representing the set of evolution operators.

For free single particle motion the evolution generator, because of the invariance with respect to four translations, should be a function of four-momenta only,

$$\hat{\mathbb{W}} \stackrel{C}{=} a^\mu \hat{p}_\mu + a^{\mu\nu} \hat{p}_\mu \hat{p}_\nu, \tag{5}$$

where C denotes required constraints, and $a^\mu, a^{\mu\nu}$ are the coefficients which, depending on the type of the particle, can be complex numbers or matrices. Typical examples are:

- spinless boson particles governed by the Klein-Gordon equation

$$\hat{W}_{KG} = \hat{p}_\mu \hat{p}^\mu, \quad (6)$$

- spin 1/2 fermion particles described by the Dirac equation

$$\hat{W}_D = \gamma^\mu \hat{p}_\mu. \quad (7)$$

Appropriate modifications of these generators can describe a wide class of physical objects.

In the non-relativistic case the standard Schrödinger motion is generated by

$$\hat{W}_S = \hat{p}_0 - H, \quad (8)$$

however, one can expect that it should be completed by a temporal part corresponding to the “kinetic” term representing the motion along the time axis and appropriate potential. The simplest version of this generalized Schrödinger generator can be written as

$$\hat{W}_{GS}(\tau) = \hat{p}_0 - \hat{\mathcal{H}}(\tau) + \left[\frac{1}{2} B_T^{-1}(\tau) \hat{p}_0^2 + V_T(\tau, x^0) \right], \quad (9)$$

The evolution generators are useful tools for construction of evolution operators not only per se, but also because they provide a unified method which is compatible with our experience and physical imagination.

3. Quantum Minkowski spacetime

As a useful example we consider some structures and features in the simplest system, namely, the Minkowski spacetime generated in the independent of τ_n state space $\mathcal{K} = L^2(R^4, d^4x)$, composed of square integrable complex functions on R^4 . The scalar product is in this case local and has the following form:

$$\langle f_2 | f_1 \rangle = \int_{R^4} d^4x f_2(x)^\star f_1(x). \quad (10)$$

The quantum spacetime is generated here by a four-vector position operator (time + 3-space operators)

$$\begin{aligned} \hat{x}^\mu &= \int_{R^4} d^4x |x\rangle x^\mu \langle x|, \\ \hat{x}^\mu f(x^0, x^1, x^2, x^3) &= x^\mu f(x^0, x^1, x^2, x^3), \end{aligned} \quad (11)$$

where $\mu = 0, 1, 2, 3$. Eigenvectors of the position operators $|x\rangle$ represent the “quantum points” in the quantum spacetime. Because the probability amplitudes $\langle x' | x \rangle = 0$ for $x' \neq x$ there is no natural geometry generated by transition probabilities among quantum points of the quantum spacetime. One can superimpose the geometry by hand. We assume here the Minkowski spacetime structure. It also means that the operators (11) are constructed with respect to a fixed but in general arbitrary observer \mathcal{O} . The $\mu = 0$ component of the four-vector position operator is the time operator,

$$\hat{t} \equiv \hat{x}^0 = \int_{R^4} dx^0 x^0 \hat{M}_T(x^0), \quad (12)$$

$$\hat{M}_T(x^0) := \int_{R^3} d^3\mathbf{x} |x\rangle \langle x|, \quad (13)$$

where $\hat{M}_T(x^0)$ projects onto a space of simultaneous events.

Observables canonically conjugated to the position observables are the four-translation generators representing the momentum operators,

$$\hat{p}_\mu := i\hbar \frac{\partial}{\partial x^\mu}. \quad (14)$$

Such operators fulfill the standard canonical commutation relations

$$[\hat{p}_\mu, \hat{x}^\nu] = i\hbar \delta_\mu^\nu. \quad (15)$$

To keep a consistent interpretation, the temporal component \hat{p}_0 of the four-momentum operator is an unbounded operator with the continuous spectrum \mathbb{R} . It has to be interpreted as the temporal momentum of the system under consideration. By analogy to the spatial components of the linear momentum operator the temporal component should describe something like a “temporal inertia” \times “speed in time” for motion along the time coordinate line. In traditional approaches either to relativistic quantum mechanics or field theory the operator \hat{p}_0 is identified with an energy operator. In PEv approach the temporal component of the four-momentum is an independent quantity.

However, equations of physical motion always (we do not know any good example when the following is not true) relate \hat{p}_0 with energy of a system under consideration, e.g., the Schrödinger equation gives the following equality $\hat{p}_0 = \hat{\mathcal{H}}$, the Klein-Gordon equation gives the following relation $\hat{p}_0^2 = m_0^2 + \hat{\vec{p}}^2$, and so on. This implies that both operators: the temporal component of the four-momentum and the energy operator can be related to the space of solutions of equations of motion for a given system. As a consequence, equations of motion of a given system allow for indirect measurement of the temporal momentum p_0 of this system.

The operators \hat{x}_ν, \hat{p}_μ obey the Heisenberg uncertainty principle in the Robertson form,

$$\text{var}(\hat{p}_\mu) \text{var}(\hat{x}^\nu) \geq \frac{1}{4} \langle i[\hat{p}_\mu, \hat{x}^\nu] \rangle^2 = \frac{\hbar^2}{4} \delta_\mu^\nu, \quad (16)$$

where $\text{var}(\hat{A}) := \langle \hat{A}^2 \rangle - \langle \hat{A} \rangle^2$ denotes the variance of \hat{A} . Using, equations of motion of a given system one can construct the appropriate uncertainty relations between energy and time. For example, for the solutions of the Schrödinger equation $\hat{p}_0 \Psi = \hat{\mathcal{H}} \Psi$ the uncertainty relation (16) reads

$$\text{var}(\hat{\mathcal{H}}) \text{var}(\hat{t}) \geq \frac{\hbar^2}{4}. \quad (17)$$

In the standard approach to quantum mechanics, where time is a parameter, neither inequality (16) nor its implication (17) do not exist.

Time as a quantum observable implies spread of wave functions $\Psi(t, \vec{x})$ in time. To have correct probability interpretation, normalization of the state $\Psi(t, \vec{x})$ is performed over the whole four-dimensional spacetime,

$$\int_{R^4} dt d^3x |\Psi(t, \vec{x})|^2 = 1. \quad (18)$$

This implies a new phenomenon that $\Psi(t, \vec{x})$ can be zero even in a large region of the spacetime but contrary to quantum mechanics with a parametric time the state $\Psi(t, \vec{x}) \neq 0$.

In the standard approach, where time is treated as a parameter normalization of $\Psi(t, \vec{x})$ is done for a fixed time over the 3D-space:

$$\int_{R^3} d^3\vec{x} |\Psi(t, \vec{x})|^2 = 1. \quad (19)$$

In this case, if the state is identically equal to zero at one instant of time, then it vanishes identically, i.e., if $\Psi(t_0, \vec{x}) = 0$ for all $\vec{x} \in R^3$, then $\Psi(t, \vec{x}) = 0$ for all t .

The characteristic time for a system being in the state $|\Psi\rangle$ can be calculated as an expectation value of the time operator,

$$t_{obs} = \langle \hat{t}; \Psi \rangle = \int_{R^4} dt d^3x t |\Psi(t, \vec{x})|^2. \quad (20)$$

The characteristic time corresponding the 3D wave function $\Psi(t, \vec{x})$ is simply given by the parameter t . The 3D probability amplitude $\Psi(t, \vec{x})$ can be interpreted as the conditional amplitude of finding the system at the space position \vec{x} assuming that system/particle is localized at time t .

In the PEv formalism one can get the probability distribution of localizing a system at a given time t . This distribution is given by the expectation value of the simultaneous events operator (13), $\text{Prob}(t) = \langle \Psi | \hat{M}_T(t) | \Psi \rangle$.

As a consequence the functions $\Psi(x) := \langle x^0, x^1, x^2, x^3 | \Psi \rangle \in \mathcal{K}$ can connect also events with space-like intervals $(x^0)^2 - \vec{x}^2 < 0$ and can lead to the breaking of the standard classical causality. Obviously, causality can be easily recovered by constraints, however, as it has been shown in the Introduction, some experiments suggest breaking of classical causality on the quantum level. An interesting experiment which supports our thinking about causality is reported in [20].

Within the PEv approach the quantum causality is realized by keeping the correct order of the subsequent steps of the evolution, labelled by the evolution parameter τ .

4. Time reversal and arrow of time

Time reversal (inversion in time) is one of the fundamental spacetime symmetry. In the standard approach to time as an evolution parameter, space inversion is represented by a unitary transformation generated by the parity operator, however, time reversal operation is a mixed type antiunitary operation forced by this model of time. Mixed type means, that formally so defined operation acts not only on variables which represent observables in the state space but also on the time parameter, which is an external quantity with respect to the state space.

In PEv formalism there are two well defined in the state space time reversal operators:

- unitary Racah's time reversal operator \mathcal{T}_R

$$\mathcal{T}_R \Psi(t, \vec{x}) := \Psi(-t, \vec{x}), \quad (21)$$

- antiunitary Wigner's time reversal operator \mathcal{T}_W

$$\mathcal{T}_W \Psi(t, \vec{x}) = \Psi(-t, \vec{x})^*. \quad (22)$$

In traditional approach the temporal component of the four-momentum was identified with energy, which is assumed to be positive. A consistency of the relativistic theory implies a fixed sign of the temporal momentum, $p_0 \geq 0$.

In PEv the temporal component of the four-momentum is a quantity independent of energy. In this case, the operator \hat{p}_0 is usually related to the energy of a system through its equations of motion and the sign of p_0 , where p_0 denotes eigenvalues of \hat{p}_0 , provides a natural arrow of time, in which $p_0 > 0$ represents opposite direction in the temporal motion than $p_0 < 0$. Let us assume the positive sign for our world as a dominant direction of time.

Using spectral decomposition of \hat{p}_0 ,

$$\hat{p}_0 = \hbar \int_{R^4} d^4k k_0 |k\rangle \langle k|, \quad (23)$$

one can easily construct two projection operators onto positive and negative time direction:

$$\hat{M}_{T+} = \int_{\mathbb{T}^4} d^4k |k\rangle \delta(k_0 \geq 0) \langle k|, \quad (24)$$

$$\hat{M}_{T-} = \int_{\mathbb{T}^4} d^4k |k\rangle \delta(k_0 \leq 0) \langle k|. \quad (25)$$

Both worlds, represented by $\hat{M}_{T+}\mathcal{K}$ and $\hat{M}_{T-}\mathcal{K}$ are orthogonal. They can be coupled by interactions.

Applying (21) to the temporal component of the linear momentum one gets $\mathcal{T}_R \hat{p}_0 \mathcal{T}_R^\dagger = -\hat{p}_0$, i.e., the Racah's time reversal operation changes arrow of time, but the Wigner's time reversal operation (22) does not change direction of time, i.e., $\mathcal{T}_W \hat{p}_0 \mathcal{T}_W^\dagger = +\hat{p}_0$.

It implies that only the Racah's time reversal operator couples both world representing the opposite direction of time:

$$\mathcal{T}_R \hat{M}_{T+} \mathcal{T}_R = \hat{M}_{T-}, \quad (26)$$

$$\mathcal{T}_R \hat{M}_{T-} \mathcal{T}_R = \hat{M}_{T+}. \quad (27)$$

An important property of the Racah's time reversal operator is that it is a self-adjoint operator in the state space and it can be considered to be a new quantum observable. The Wigner's time reversal operator does not have this important feature. This provides a new, probably important, symmetry in the evolution procedure. For example, the Klein-Gordon type evolution generator (6) is invariant with respect to both Racah's and Wigner's time reversal operators, but the Dirac type motion (7) is invariant only with respect to Wigner's time reversal operation. This new symmetry and a new quantum observable requires further analysis.

As an example, for a single particle case a wave function moving in positive time direction can be written as a "half"-Fourier transform,

$$\Psi_+(x) = \int_0^\infty dk_0 \gamma(k_0, \vec{x}) e^{-ik_0 t}. \quad (28)$$

Assuming in (28) the temporal profile in the form of the rectangular pulse:

$$\gamma(k_0, \vec{x}) = N \chi_{[0, k_{0M}]}(k_0) \Phi_0(\vec{x}), \quad (29)$$

where the characteristic function $\chi_{[0, k_{0M}]}(k_0) = 1$ if $k_0 \in [0, k_{0M}]$, otherwise $\chi_{[0, k_{0M}]}(k_0) = 0$, one gets the following wave function:

$$\Psi_+(x) = \Phi_0(\vec{x}) \sqrt{\frac{k_{0M}}{2\pi}} e^{-i\frac{k_{0M}}{2} t} j_0\left(\frac{1}{2} k_{0M} t\right), \quad (30)$$

where $j_0(x) := \sin(x)/x$ is the spherical Bessel function.

Acting with the Racah's time reversal on the function (30) one gets the function with opposite arrow of time,

$$\mathcal{T}_R \Psi_+(x) = \Phi_0(\vec{x}) \sqrt{\frac{k_{0M}}{2\pi}} e^{+i\frac{k_{0M}}{2} t} j_0\left(\frac{1}{2} k_{0M} t\right). \quad (31)$$

On the other hand, the Wigner's time reversal does not change the arrow of time but results in the complex conjugation of the spatial part of the wave function,

$$\mathcal{T}_W \Psi_+(x) = \Phi_0(\vec{x})^* \sqrt{\frac{k_{0M}}{2\pi}} e^{-i\frac{k_{0M}}{2} t} j_0\left(\frac{1}{2} k_{0M} t\right). \quad (32)$$

If both states (30) and (32) have the same energy, they are often referred to as the Kramer's degeneration. Both states represent the same probability distribution.

Both transformations are well defined in the physical state space and finally only appropriate experiments can decide which of two, maybe both, symmetry is fulfilled.

One can expect, that the new evolution formalism may lead to some revision of the already performed experiments.

5. Conclusions

We have presented a new approach to the quantum evolution, called the Projection Evolution (PEv), and described in details in [4], see also references therein. In the present report we focus on a more extended interpretation and a few new features of the PEv model.

The PEv model is based on an idea that our Universe is changing spontaneously, which results in the creation of not only physical objects, but spacetime itself. As a consequence time has to be considered on the same footing as other quantum observables.

This is supported by a series of experiments, a few of them is shortly described in the Introduction: the experiments related to Bell's inequality in space and time domains, delayed choice type phenomena and excellent experiments showing interference in time. More information can be found in [4] and references therein. The non-locality of quantum mechanics is its already accepted feature. In PEv model this non-locality is even stronger, it is extended on the time domain. Some experiments suggest even more, that classical understanding of causality is broken on quantum level of our world.

The PEv idea allows to construct the spacetime position four-operator. Its explicit form is dependent on the model under consideration. In this paper a short example of the structureless Minkowski spacetime is considered. An important new independent observable, namely the temporal component of the linear momentum operator \hat{p}_0 is described. It is usually coupled to energy through equations of motion of a system under consideration. In addition, it allows to introduce a universal time arrow.

The last section is devoted to the time reversal transformations in spacetime. In this paper, we present only short introduction to the analysis of the time reversal which is a very important symmetry in our world.

The PEv formalism opens new fields of symmetry analysis, it is due to the fact that time seems to be a quite standard quantum observable.

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