Quantum Time

A. Góźdź

Institute of Physics
University of Maria Curie–Skłodowska, Lublin, Poland

PoToR–10, 16–20 September 2024, Kazimierz Dolny

Preliminaries

Configuration and phase space of a physical system

Configuration space

Configuration space := Space spanned by all variables used to describe physical system. It can contain redundant variables.

Phase space

Configuration space containing variables and their duals.

Degree of freedom

Degree of freedom = Esential variable required for description of a given physical system.
Full set of degrees of freedom create minimal configuration space required to describe corresponding physical system.

Spacetime observables

Spacetime position observable

For many years time was treated in physics as a universal parameter which allows the observer to divide the reality into past, present, and future. However, to obtain GR+QM one needs to treat time and space on the same footing.

However,

Quantum time

Experimental observations imply: Time should be a quantum observable, not a parameter.

Quantum time idea described in:

1. A. Góźdź, M. Góźdź, A. Pędrak, Quantum Time and Quantum Evolution, Universe 2023, 9, 256.

2. A. Góźdź and M. Góźdź, Quantum Clock in the Projection Evolution Formalism, Universe 2024, 10, 116.

A few experiments

Delayed choice phenomena

”Delayed choice”

J.A. Wheeler proposed a Gedankenexperiment, the so called “delayed choice problem”.

Wheeler, J.A., The “Past” and the “Delayed-Choice” Double-Slit Experiment, in Mathematical Foundations of Quantum Theory, ed. Marlow, A.R., Academic Press, New York, USA, 1978, 9–48; Wheeler, J.A., Law without law, in Quantum Theory and Measurement, Wheeler, J.A. and Zurek W.H., Princeton University Press, 1984, 182–213

”Quantum eraser”

Double slit experiment with quantum eraser.
The effect was visible even when the changes introduced to the experimental setup led to acausal events.

Ho Kim, Y. and Yu, R. and Kulik, S.P. and Shih, Y. and Scully, M.O., Delayed “Choice” Quantum Eraser, Phys. Rev. Lett., 84, 2000, 1–5

„Wheeler's Gedankenexperiment"

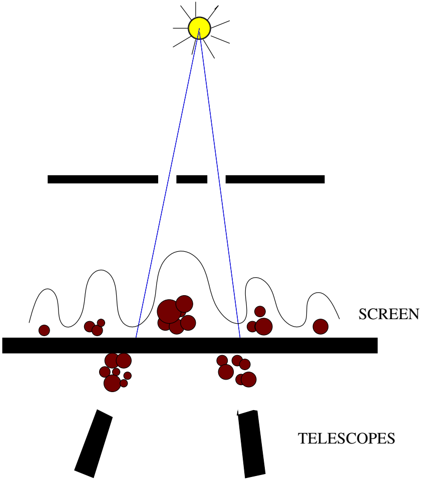


Figure: Particle versus interference picture

Delayed choice phenomena

The 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 begining of its evolution forgeting what happend till time t" and it evolves in a way compatible with this new conditions, though it is an **acausal** event.

Teleportation 1/2

Teleportation

Teleportation – was conducted using entangled pairs of photons separated by 144 km. Even though the particles were causally disconnected, **the changes made in the first laboratory were affecting the second particle**.

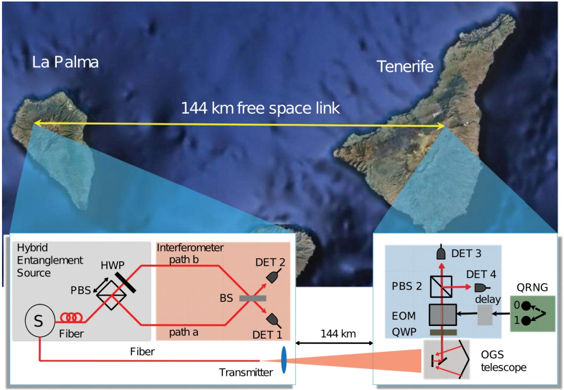
Ursin, R. and Tiefenbacher, F. and Schmitt-Manderbach, T. and Weier, H. and Scheidl, T. and Lindenthal, M. and Blauensteiner, B. and Jennewein, T. and Perdigues, J. and Trojek, P. and Ömer, B. and Fürst, M. and Meyenburg, M. and Rarity, J. and Sodnik, Z. and Barbieri, C. and Weinfurter, H. and Zeilinger, A., Entanglement-based quantum communication over 144 km, Nature Physics, 3, 2007, 481–486

More than 90 times faster signal than c is required to connect both events.

Teleportation 2/2

Xiao-Song Ma, et al., Quantum teleportation between the Canary Islands La Palma and Tenerife over both quantum and classical 144-km free-space channels.

Nature 489, 269–273 (13 September 2012) doi:10.1038/nature11472



Temporal interference 1/7

- If time in the quantum regime should be treated as a coordinate, and in fact a quantum observable, all physical objects' states have to have some "width" in the time direction, $[\hat{p}_0, \hat{x}^0]$ (indirectly, the energy-time uncertainty relation).
- This means that it should be possible to observe the interference of quantum objects through their overlap in time

1. Houser, U. and Neuwirth, W. and Thesen, N., Time-dependent modulation of the probability amplitude of single photons, Phys. Lett. A, 49, 1974, 57–58

2. Lindner, F. and Schätzel, M.G. and Walther, H. and Baltuška, A. and Goulielmakis, E. and Krausz, F. and Milošević, D.B. and Bauer, D. and Becker, W. and Paulus, G.G., Attosecond Double-Slit Experiment, Phys. Rev. Lett., 95, 2005, 040401

3. Tirole, R.; Vezzoli, S.; Galiffi, E.; Robertson, I.; Maurice, D.; Tilmann, B.; Maier, S.A.; Pendry, J.B.; Sapienza, R. Double-slit time diffraction at optical frequencies. Nat. Phys. 2023, 1–4.

Temporal interference 2/7

U. Houser, W.Neuwirth, N. Thesen: Phys. Lett. A49 (1974) 57.

- A beam of the Mösbauer photons is emitted with $E_\gamma = 14.4$ keV from the excited state (lifetime $\tau = 141$ ns) of ^{56}Fe.
- This beam is modulated by a chopper with 2500 wholes.
- One gets about 3000 γ-counts i.e. 1 γ passes the slit per $3000/\tau \approx 2000$ of lifetimes τ – these photons are well separated.
- One observes the interference fringes on the "energy screen"
- The only explanation: the single photon interfere with itself.
- The time cannot be interpreted as a parameter.

Temporal interference 3/7

Volume 49A, number 1 PHYSICS LETTERS 12 August 1974

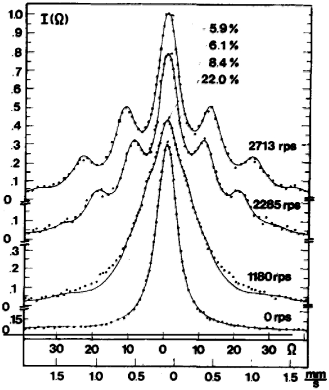


Fig. 2. Experimental results compared with theory. At the wings neighbouring channels are accumulated.

where $f(\Omega)$, $g(\Omega)$ and $h(\Omega)$ stand for

$$f(\Omega) = 1 - 2\exp(-T)\cos\{\Omega T\} + \exp(-2T)\,.$$

$$g(\Omega) = 1 - 2\exp(-T)[\sinh\{T\rho\}\cdot\cos\{\Omega T(1-\rho)\} + \sinh\{T(1-\rho)\}\cdot\cos\{\Omega T\rho\}] - \exp(-2T)\,,$$

$$h(\Omega) = 2\exp(-T)[\cosh\{T\rho\}\cdot\sin\{\Omega T(1-\rho)\} + \cosh\{T(1-\rho)\}\cdot\sin\{\Omega T\rho\} - \sin\{\Omega T\}]\,.$$

The natural variables $T = \Delta/2\tau$, $\Omega = (E-E_0)/(\Gamma_0/2)$ refer to the lifetime $\tau = \hbar/\Gamma_0$ = 141 nsec and the linewidth Γ_0 of the excited state of the source. The formula represents a Lorentzian central line, reduced in weight by the duty cycle $\rho = \Delta_{\mathrm{open}}/\Delta = 1 - \Delta_{\mathrm{closed}}/\Delta$ plus oscillating, non-Lorentzian terms symmetric to $\Omega = 0$. The solid lines in fig. 2 represent the theoretical transmission spectra, normalized to $I(\Omega{=}0) = 1$. These transmission spectra are given by 95 % of the modulated emission spectra $I(\Omega,T,\rho)$ convoluted with the resolution of the Mössbauer absorber, plus an unmodulated contribution of 5 %. Fig. 2 includes also the absolute resonance absorption of the central peak as a function of rps. All experimental constants factors as ρ, the transmission and the energy calibration as

Figure: Hauser exp., Emission through the time slits

Temporal interference 4/7

quant-ph/05033165 v2, 2005, F. Lindner et al., PRL 95 (2005) 040401-1

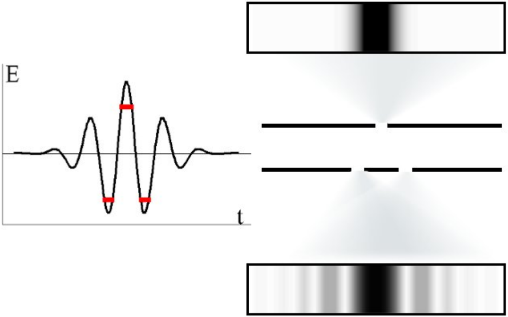


Figure: Emission through the time slits (Fig. O.P.)

Temporal interference 5/7

quant-ph/05033165 v2, 2005, F. Lindner et al.

Attosecond double-slit experiment

F. Lindner,[1] M. G. Schätzel,[1] H. Walther,[1,2] A. Baltuška,[1] E. Goulielmakis,[1]
F. Krausz,[1,2,3] D. B. Milošević,[4] D. Bauer,[5] W. Becker,[6] and G. G. Paulus[1,2,7]
[1] *Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[2] *Ludwig-Maximilians-Universität München, 85748 Garching, Germany*
[3] *Institut für Photonik, Technische Universität Wien, Gusshausstr. 27, A-1040 Wien, Austria*
[4] *Faculty of Science, University of Sarajevo, Zmaja od Bosne 35, 71000 Sarajevo, Bosnia and Hercegovina*
[5] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[6] *Max-Born-Institut, Max-Born-Str. 2a, 12489 Berlin, Germany and*
[7] *Department of Physics, Texas A&M University, College Station, TX 77843-4242*
(Dated: June 30, 2005)

A new scheme for a double-slit experiment in the time domain is presented. Phase-stabilized few-cycle laser pulses open one to two windows ("slits") of attosecond duration for photoionization. Fringes in the angle-resolved energy spectrum of varying visibility depending on the degree of which-way information are observed. A situation in which one and the same electron encounters a single and a double slit at the same time is discussed. The investigation of the fringes makes possible interferometry on the attosecond time scale. The number of visible fringes, for example, indicates that the slits are extended over about 500 as.

The conceptually most important interference experiment is the double-slit scheme, which has played a pivotal

3

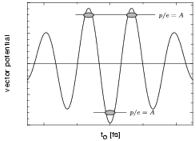


FIG. 4: Vector potential of a −sine-like few-cycle pulse. The temporal slits are given by the condition $p - eA(t_0) = 0$. For a −sine-like pulse, this leads to a double slit in the negative direction (since $e = -|e|$) and a single slit in the opposite direction. Each slit can be resolved into a pair of slits.

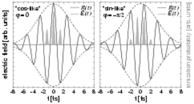


FIG. 1: Temporal variation of the electric field $\mathcal{E}(t) = \mathcal{E}_0(t)\cos(\omega t + \varphi)$ of few-cycle laser pulses with phase $\varphi = 0$ ("cosine-like") and $\varphi = -\pi/2$ ("sine-like"). In addition, the field ionization probability $R(t)$, calculated at the experimental parameters, is indicated. Note that an electron ionized at $t = t_0$ will not necessarily be detected in the opposite direction of the field $\mathcal{E}$ at time t_0 due to deflection in the oscillating field.

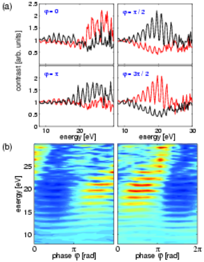
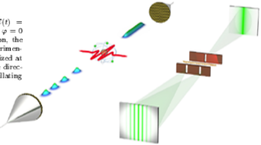


FIG. 2: Photoelectron spectra of argon measured with 6-fs laser pulses for intensity 1×10^{14} W/cm² as a function of the



Temporal interference 6/7

Tirole, R., Vezzoli, S., Galiffi, E. et al. Double-slit time diffraction at optical frequencies. Nat. Phys. 19, 999–1002 (2023).
https://doi.org/10.1038/s41567-023-01993-w ;

Next slide: the figure shows an idea of this experiment. It is taken from: Tirole, R., Vezzoli, S., Galiffi, E. et al. Double-slit time diffraction at optical frequencies, arXiv:2206.04362v2

Temporal interference 7/7

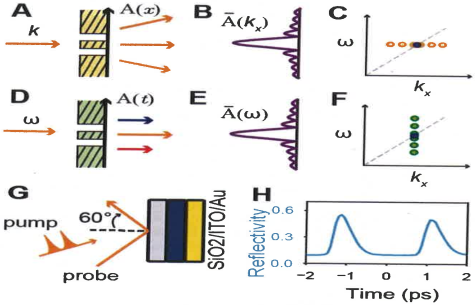
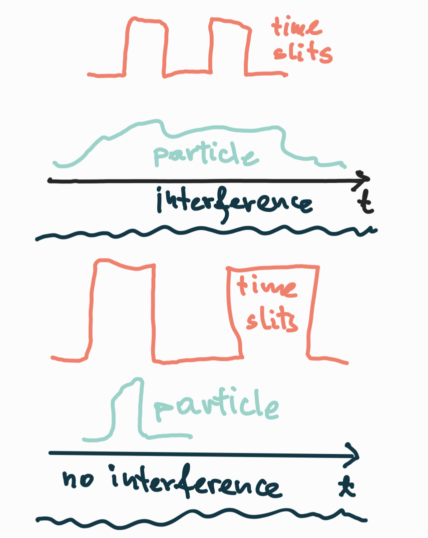


Figure 1. **Concept and realization of the double-slit diffraction experiment in time. (A)** Conventional spatial double-slit experiment: as light diffracts from a spatial double slit, **(B)** the aperture changes the beam's in-plane momentum k_x, corresponding to **(C)** a horizontal transition in the dispersion diagram. **(D)** Temporal double-slit experiment: as light interacts with a double time modulation, **(E)** an aperture in time acts on the frequency ω of the beam. **(F)** The transition is now vertical in the dispersion diagram. **(G)** Experimental realization: pump and probe beams are incident close to 60 deg onto a 40 nm ITO slab on glass, coated with a 100 nm gold film. **(H)** Temporal change of the sample reflectivity (blue line) with a 2.3 ps separation between the slits.

Temporal interference – under which condition?

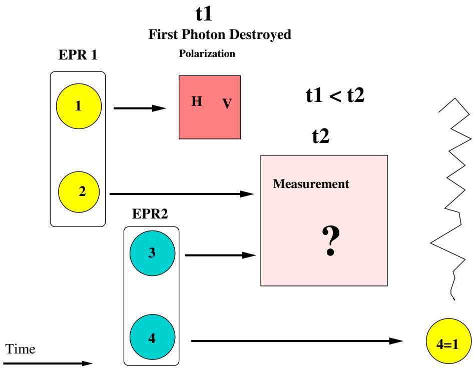


EPR between two moments 1/1

Temporal Entanglement

There exists entanglement over the time dimension.

E. Megidish et al., Entanglement Between Photons that have Never Coexisted. arXiv:1209.4191v1 [quant-ph] 19 Sep 2012



Projection Evolution (PEv)

Time is an important degree of freedom of every physical system.

To describe evolution in which time is a quantum observable a new formalism is required.

Extended configuration/phase space $\mathbf{X}$

Four position and momentum

Quantum time and spatial position operators are components of spacetime position operator.
Similarly, temporal and spatial momenta are components of four momentum operator.
Obviously, with respect to a given observer.

Extended configuration space

Extended configuration space should contain spacetime position observable and in case of phase space four momentum observable.
In general, one can use their functions – generalized variables.

Projection evolution 1/3

!!! The changes principle:

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

The PEv operators at the evolution step τ_n are defined as a family of transformations:

$$\text{₣}(\tau_n; \nu, \cdot) : \mathcal{T}_1^+(\mathcal{K}(\tau_{n-1})) \to \mathcal{T}^+(\mathcal{K}(\tau_n)),$$

Choi, M. Completely positive linear maps on complex matrices. Linear Algebra Its Appl. 1975, 10, 285–290.

Kraus, K.; Böhm, A.; Dollard, J.; Wooters, W. States, Effects and Operations: Fundamental Notions of Quantum Theory; Springer: Berlin/Heidelberg, Germany, 1983

where $\mathcal{T}^+(\mathcal{K}(\tau_n))$ is the quantum state space at the evolution step τ_n.

τ_n enumerates subsequent changes of quantum states – it is a global ordering parameter – it is not TIME !

Projection evolution, chooser 2/3

The generalized Lüders projection postulate is proposed as the principle for the evolution (chooser):

$$\rho(\tau_n;\nu_n) = \frac{\mathbb{F}(\tau_n;\nu_n,\rho(\tau_{n-1};\nu_{n-1}))}{\mathrm{Tr}\left(\mathbb{F}(\tau_n;\nu_n,\rho(\tau_{n-1};\nu_{n-1}))\right)}.$$

Probability distribution

The probability distribution for the chooser is given by the quantum mechanical transition probability from the previous to the next state: $\rho(\tau_{n-1};\nu_{n-1}) \to \rho(\tau_n;\nu_n)$.

Kraus operators:

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

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.

Projection evolution, chooser 3/3

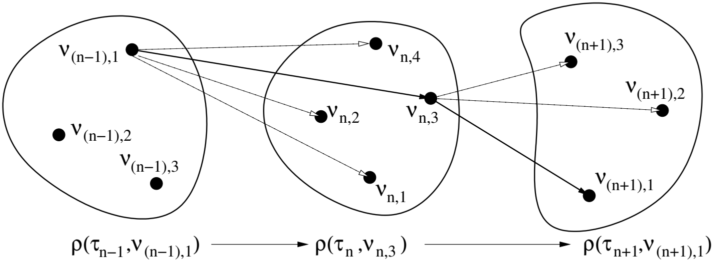


Figure: The density matrix ρ is randomly chosen at each evolution step τ from the possible states labeled by $\mathcal{Q}_m = \{\nu_{m,1}, \nu_{m,2}, \dots\}$, where $m = n-1, n, n+1$.

Configuration space – simplified version

Configuration space support

1. Let us identify the configuration space $\mathbf{X} \subset \mathbb{R}^{N_U}$ with a group of motions G, i.e., any parametrization param(G) of the group G can represents $\mathbf{X} = \mathrm{param}(\mathrm{G})$.
2. Let us assume a four dimensional spacetime support $\mathbf{X}_{ST} \subset \mathbb{R}^4$.
3. Let $(\mathbf{X}, \mathbf{X}_{ST}, \pi_{ST})$ be a bundle with the base $\mathbf{X}_{ST}$ and the projection $\pi_{ST} : \mathbf{X} \to \mathbf{X}_{ST}$.

Every group element $g \in \mathrm{G}$ can be parametrized by

- the spacetime position $x \in \mathbf{X}_{ST}$,
- intrinsic properties $\tilde{\xi} = (\xi_4, \xi_5, \ldots, \xi_{N_U}) \in \pi_{ST}^{-1}(x)$ of the spacetime point x.

$$\bigcup_{x \in \mathbf{X}_{ST}} \pi_{ST}^{-1}(x) = \mathbf{X}$$

Quantum configuration space (simplified)

Let us consider an irreducible representation $T(\tau_n) : \mathrm{G} \to \mathcal{K}(\tau_n)$ of the group of motion G in the state space $\mathcal{K}(\tau_n)$ of a physical system.

Coherent states

The states $|\tau_n; g\rangle = T(\tau_n; g)|\tau_n; \Phi_0\rangle$,
where $|\tau_n; \Phi_0\rangle$ is a cyclic (fiducial) vector,
can be interpreted as "quantum points" of the quantum configuration space $\mathbf{X}_Q$.

Every state can be expressed as a combinations of the quantum points $|\tau_n; g\rangle$ of the configuration space:

$$|\tau_n; f\rangle = \int_{\mathrm{G}} d\mu(g) f(g) |\tau_n; g\rangle .$$

Full description by QMA(G) algebra!!!!

Quantum spacetime

Quantum spacetime

The quantum spacetime is represented by the states parametrized by the points x:

$$\mathbf{X}_{ST} \ni x \to \{|\tau_n; g(x,\xi)\rangle : \xi = \pi_{ST}^{-1}(x)\}; \quad \text{Hilbert}\{\}?$$

In general, the single point x of the spacetime can be represented by a set of quantum states with various intrinsic properties, i.e., a degeneration of the spacetime point is possible.

"Quantum geometry"

The nonzero amplitudes $\langle g_k | g_l \rangle \neq 0$ generate the natural paths in the configuration space.

Quantum Minkowski spacetime (structureless – simplified version)

Structureless Minkowski space 1/3

The Minkowski space is generated by a set of the spacetime Lorentz four–vector position operator (time + 3-space operators)

$$\hat{x}^\mu = \int_{\mathrm{T}^4} d^4x|x\rangle x^\mu \langle x|$$
$$\hat{x}^\mu f(x^0, x^1, x^2, x^3) = x^\mu f(x^0, x^1, x^2, x^3)$$

with respect to a fixed but arbitrary observer $\mathcal{O}$.

Time operator

$$\hat{t} \equiv \hat{x}^0 = \int_{\mathrm{T}^4} dx^0 x^0 \hat{M}_T(x^0)$$
$$\hat{M}_T(x^0) := \int_{\mathrm{T}^3} d^3\mathbf{x}|x\rangle\langle x|$$

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

Structureless Minkowski space 2/3

The four-translation generators represent the momentum operators

$$\hat{p}_\mu := i\hbar \frac{\partial}{\partial x^\mu}$$

Note the "canonical" commutation relations

$$[\hat{p_\mu}, \hat{x^\nu}] = i\hbar \delta_\mu^\nu$$

To keep a consistent interpretation, the zero component $\hat{p}_0$ describes the temporal momentum of the system under consideration. It gives:

- Arrow of time: either $p_0 > 0$ or $p_0 < 0$.
- By analogy to 3D, the value of p_0 determines "temporal inertia" × "speed in time" of motion in time.

Structureless Minkowski space 3/3

$E \leftrightarrow p_0$

The traditional interpretation of p_0 as the energy holds only in the case when the equations of motion relate p_0 directly to the energy of the system, e.g.,
on solutions of the Schrödinger equation $\hat{p}_0 = \hat{\mathcal{H}}$,
on solutions of the Klein-Gordon equation $p_0^2 = m_0^2 + \vec{p}^2$, etc.

Measurement of p_0

Equation of motions allow for indirect measurement of the temporal momentum p_0.

Uncertainty principle

Heisenberg uncertainty principle

The operators $\hat{x}_\nu, \hat{p}_\mu$ obey the Heisenberg uncertainty principle in the Robertson form

$$\mathrm{var}(\hat{p}_\mu)\ \mathrm{var}(\hat{x}^\nu) \geqslant \frac{1}{4}\left\langle i[\hat{p}_\mu, \hat{x}^\nu]\right\rangle^2 = \frac{\hbar^2}{4}\delta^\nu_\mu, \tag{1}$$

where $\mathrm{var}(\hat{A}) := \left\langle \hat{A}^2 \right\rangle - \left\langle \hat{A} \right\rangle^2$ denotes variance of $\hat{A}$.

Remark

In the standard approach to QM, where time is a parameter, for $\mu = \nu = 0$, i.e. for $\hat{x}^0, \hat{p}_0$, this inequality does not exist.

Causality

Causality 1/2

Broken causality

The functions $\Psi(x) := \langle x^0, x^1, x^2, x^3 | \Psi\rangle \in \mathcal{K}_X$ in their general form connect also events with space-like intervals $(x^0)^2 - \vec{x}^2 < 0$ $\Rightarrow$ causality is broken.

Causality can be easily recovered by constraints, HOWEVER,

Experiment

Yin et. al., Lower Bound on the Speed of Nonlocal Correlations without Locality and Measurement Choice Loopholes, Phys. Rev. Lett. 110, 2013, 260407

suggests, that it is a natural phenomenon that the classical causality is broken in the quantum world.

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

Causality, Temporal Bell's inequality 2/2

M. Zych, F. Costa, I. Pikovski and Č. Brukner: Bell's theorem for temporal order, Nature Communications, (2019)10:3772 https://doi.org/10.1038/s41467-019-11579-x.

> "... We consider a thought experiment with massive body in a spatial superposition and show how it leads to entanglement of temporal orders between time-like events. ... temporal order cannot be described by any pre-defined local variable. A classical notion of a causal structure is therefore untenable in any framework compatible with the basic principles of quantum mechanics and classical general relativity."

Waiting for real experiment!

Single particle wave functions

Single particle wave functions 1/2

3D – conditional probability

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

$\Psi(t = t_0, \vec{x}) = 0$, then $\Psi(t, \vec{x}) \equiv 0$ for every t.

If $\Psi(t_0, \vec{x}) = 0$ then $\Psi(t, \vec{x}) = 0$ for all t.

4D – density probability

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

$\Psi(t, \vec{x})$ can be zero even in large regions of the spacetime and $\Psi(t, \vec{x}) \not\equiv 0$.

Single particle wave function 2/2

3D

The characteristic time corresponding the wave function $\Psi(t, \vec{x})$ is t. Time is a parameter.

4D

The characteristic time corresponding the wave function $\Psi(t, \vec{x})$ is determined by the expectation value of the time operator $\hat{t}$

$$\left\langle \hat{t}; \Psi \right\rangle = \int_{R^4} dt\, d^3x\, t\, |\Psi(t, \vec{x})|^2$$

π^+ temporal interference PEv description

Temporal interference, PEv approach 1/4

1. The pion π^+ is produced with the initial three-momentum $\vec{k} = (0, 0, -k_z)$.
2. On its way to the detector it has to pass a slit which opens twice in the same spatial location.
3. The slit has spatial widths $\delta_1 = \delta_2 = d$ in the plane perpendicular to the direction of motion, the width δ_3 unimportant.
4. We denote the time width of the opened slit by δ_T, and the time between the two openings by $\epsilon_T = t_2 - t_1$.
5. The mass of π^+ is $m_\pi \approx 139$ MeV. Its half-life is $t_\pi = 3.95 \cdot 10^7\ \text{eV}^{-1}$, which implies the mass spread of the order of $\Gamma \sim 1/t_\pi \approx 2.5 \cdot 10^{-8}$ eV (almost exactly on its mass shell).
6. Assuming the initial Klein-Gordon state of the particle is given by $k_0^2 = m_\pi^2 + k_z^2$, the state seen by the detector will be $\kappa_0^2 = m_\pi^2 + \kappa_1^2 + \kappa_2^2 + k_z^2$.

Temporal interference, PEv approach 2/4

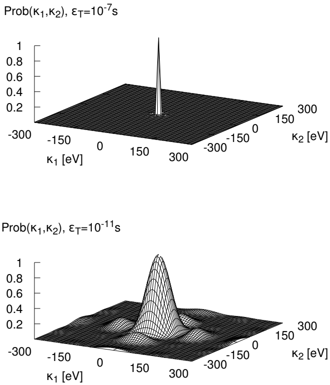


Figure: The detection probability as a function of κ_1 and κ_2 for different values of the opening times.

Temporal interference, PEv approach 3/4

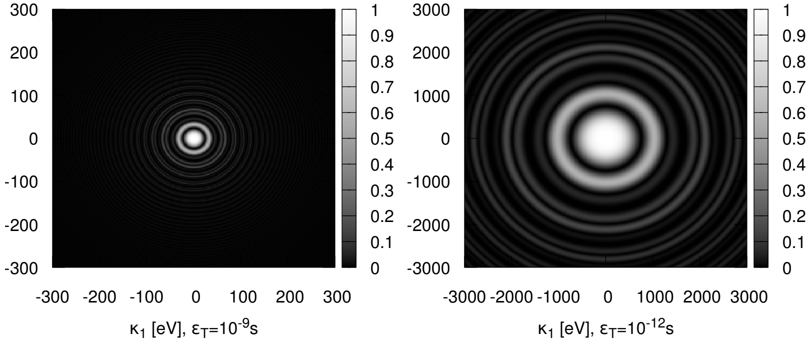


Figure: The temporal part of $\mathrm{Prob}(\kappa_1, \kappa_2)$ for different values of the opening times ϵ_T.

Temporal interference, PEv approach 4/4

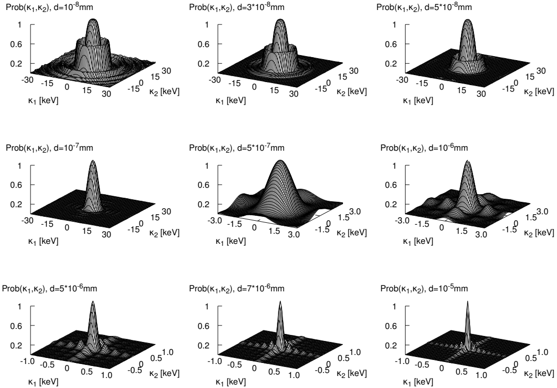


Figure: The detection probability as a function of κ_1 and κ_2 for different spatial widths of the slit. Here $d = \delta_1 = \delta_2$. The time between the openings is set to $\epsilon_T = 10^{-14}$ s and the slit is open for $\delta_T = \epsilon_T/3$.

„Future” and ”Past” delayed choices

A. Góźdź and K. Stefańska (2008):
doi:10.1088/1742-6596/104/1/012007
M. Góźdź, A. Góźdź, A.A. Gusev, and S.I. Vinitsky (2018):
doi: 10.1134/S1063778818060157

„Wheeler's Gedankenexperiment" (1/2)

- Photon is emitted by a distant star.
- Assume that the photon have to pass the massive star in its motion towards the Earth. The gravitational lensing acts as a double–slit device.
- The photon continues on its way to the Earth.
- The photon can be observed by:
  - a directional telescope $\Rightarrow$ particle
  - a screen $\Rightarrow$ interference, wave.
- "*Thus one decides the photon shall have come by one route or by both routes after it has already done its travel*", A.J.Wheeler, in Quantum Theory and Measurement, pp.182-213, J. A. Wheeler and W. H. Zurek edit., (Princeton University Press, 1984).

„Wheeler's Gedankenexperiment"

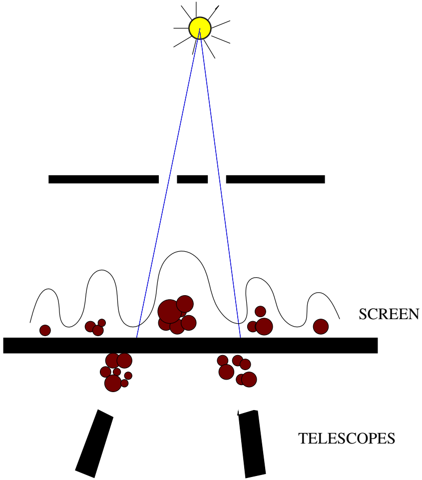
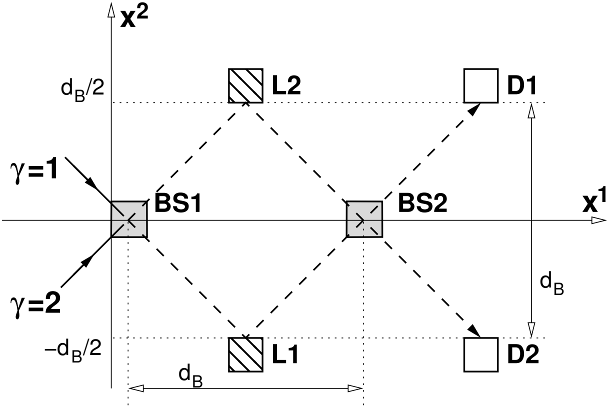


Figure: Particle versus interference picture

Interferometer "future"



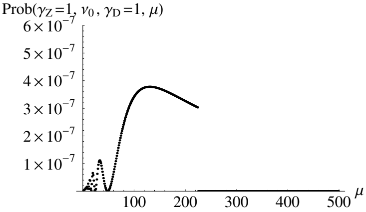
Wheeler's delayed choice 1/4

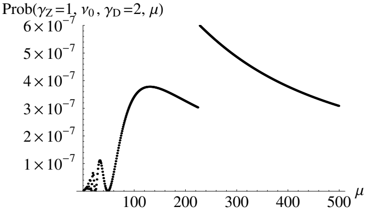
- A single particle enters the first port of the BS1.
- In the absence of the second beam splitter (BS2) the detector D=(D1,D2) is able to "check" the path on which the particle travels.
- After insertion of the second beam splitter the "Welcher-Weg"information is irreversibly lost and one can observe some interference phenomena in the detector D. It can be interpreted that the particle has traveled both paths.
- According to Wheeler one can decide "whether to put in the second beam splitter or take it out at very last minute. Thus one decides whether the photon shall have come by one route, or by both routes after it has already done its travel"

Wheeler's delayed choice (2/4)

- The particle can be localized in the interval $< 0, T > \Rightarrow$ the detection probability for times $t \geqslant T$ and before $t = 0$ is equal to 0.
- Let us denote t_b as a moment of insertion of BS2.
- $t_b \leqslant 0 \Rightarrow$ particle detected only in the second channel. The particle passes through both beam splitters.
- $t_b \geqslant T$. The only BS1 "exists". The particle detected in both channels with equal probabilities.
- $0 \leqslant t_b \leqslant T$. The BS2 is inserted after the particle "had to choose" a path for its motion. The probability of detection dependent on the time μ.
  - $(\mu + 1)\delta_T \leqslant t_b \Rightarrow$ the particle is detected before insertion of the BS2. The particle detected in both channels with equal probabilities.
  - $(\mu + 1)\delta_T > t_b \Rightarrow$ the particle is detected only in the second channel. This behaviour is independent of the actual value of t_b, as it is observed in delayed–choice experiments.

Wheeler's delayed choice(3/4)

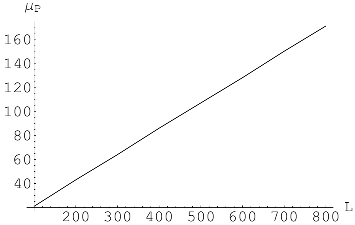




The probability of particle detection in the channels 1 and 2 at the time μ

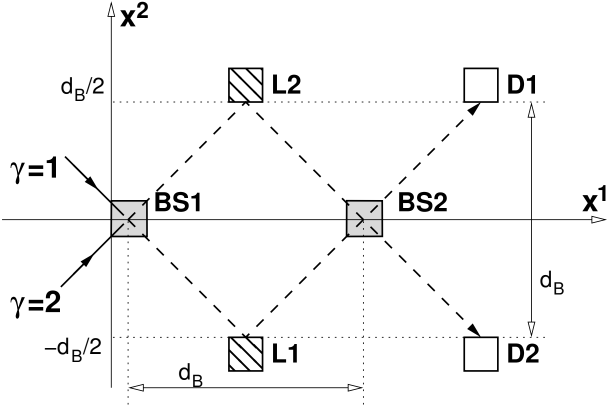
Wheeler's delayed choice(4/4)

A dependence of the most probable detection time μ_P as a function of distance between the source and the detector L:



The result suggests, as expected, that the particle is moving with constant velocity. Though time is an observable we get classical–like relation $L = v_0\, t$, where $t = \delta_T\, \mu$

Interferometer "past"



”Past” delayed choice 1/3

- A single particle enters the first port of the BS1.
- In the absence of the first beam splitter (BS1) the detector D=(D1,D2) is able to “check” the path on which the particle travels.
- After insertion of the first beam splitter the “Welcher-Weg in the past” information is irreversibly lost and one can observe some interference phenomena in the detector D. It can be interpreted that the particle has traveled both paths – quantum eraser.

"Past" delayed choice 2/3

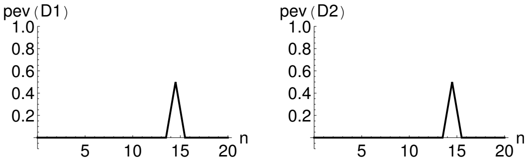


Figure: Probabilities of detecting the particle by the detectors when BS1 is absent.

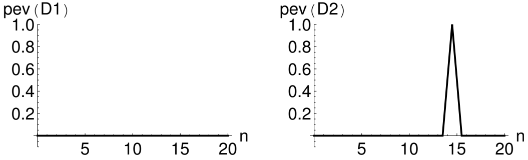


Figure: Probabilities of detecting the particle by the detectors when BS1 is present.

"Past" delayed choice 3/3

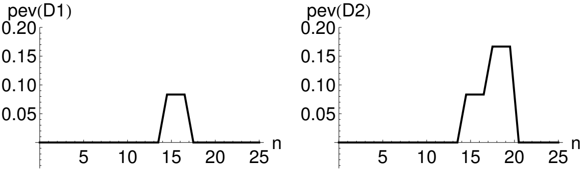


Figure: Probabilities of detecting the particle by the detectors, when BS1 is switched on during the particle's travel through the interferometer.

Arrow of time

Operator $\hat{p}_0$ 1/5

Sign of $\hat{p}_0$ determines the unique arrow of time.
Spectral decomposition:

$$\hat{p}_0 = \int_{\mathrm{T}^4} d^4p\, p_0 |p\rangle\langle p|$$

Projections onto positive and negative time direction:

$$\hat{M}_{T+} = \int_{\mathrm{T}^4} d^4p\, |p\rangle\, \chi(p_0 \geqslant 0)\, \langle p|$$

$$\hat{M}_{T-} = \int_{\mathrm{T}^4} d^4\, |p\rangle\, \chi(p_0 \leqslant 0)\, \langle p|$$

Time reversal 2/5

Two time reversal operations:

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

$$\mathcal{T}_R \Psi(t) := \Psi(-t)$$

- Wigner's time reversal operator $\mathcal{T}_R$ is antiunitary:

$$\mathcal{T}_W \Psi(t) = \Psi(-t)^\star$$

Time reversal of time arrow projection operators $\hat{M}_{T\pm}$ 3/5

Racah's time reversal changes time arrow direction:

$$\mathcal{T}_R \hat{M}_{T+} \mathcal{T}_R = \hat{M}_{T-}$$
$$\mathcal{T}_R \hat{M}_{T-} \mathcal{T}_R = \hat{M}_{T+}$$

If $\hat{M}_{T+}\Psi = \Psi$ then $\hat{M}_{T+}(\mathcal{T}_R\Psi) = 0$, i.e., Racah's $\mathcal{T}_R$ change the time direction.
If $\hat{M}_{T+}\Psi = \Psi$ then $\hat{M}_{T-}(\mathcal{T}_W\Psi) = 0$, i.e. Wigner's $\mathcal{T}_W$ does not change the time direction.

Functions moving in positive time direction 4/5

A good representant of functions moving in positive time direction is:

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

Assume the temporal rectangular pulse:

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

Then

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

Functions moving in positive time direction 5/5

Racah's time reversal:

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

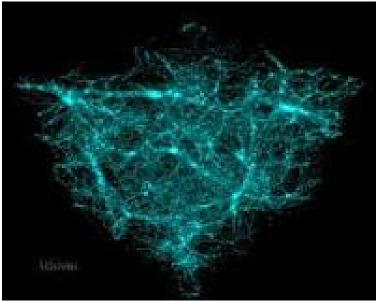
Wigner's time reversal do not change arrow of time, but gives complex conjugated spatial part (Kramer's degeneration):

$$\mathcal{T}_W \Psi_+(x) = \Phi_0(\vec{x})^\star \sqrt{\frac{k_{0M}}{2\pi}}\, e^{-i\frac{k_{0M}}{2}\,t} j_0(\frac{1}{2} k_{0M}\, t)$$

Both trnasformations do not change the corresponding probability distributions: $|\Psi_+(x)|^2 = |\mathcal{T}_R \Psi_+(x)|^2 = |\mathcal{T}_W \Psi_+(x)|^2$

Dark Matter and Dark Energy hypothesis ????????????????

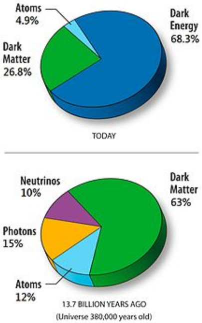
Dark Matter



Dark mater ?

Exotic states different from zero only for extremaly short pulses can be candidate for dark matter.

Dark energy



Dark energy

Interaction energy of two parts of the Universe: one with $p_0 > 0$ second with $p_0 < 0 \Rightarrow$ Total $P_0 = 0$.

Actual Collaboration

A. Pędrak & W. Piechocki
National Centre for Nuclear Research, Warsaw, Poland

A. Cieślik & P. Mach
Department of General Relativity and Astrophysics Institute of Theoretical Physics, Jagellonian University Łojasiewicza 11, 30-348 Krakow, Poland

SUMMARY

- (The group of motions G) + (Elementary probability amplitude function $\langle g|g'\rangle$) creates a quantum configuration space.
  $\Rightarrow$ Generation of the spacetime as a part of a configuration space (background independence).
- Quantum evolution is a stochastic process (PEv).
- The quantum time is a quantum observable.
  $\Rightarrow$ covariance of spacetime position operator.
- The quantum configuration space is represented by
  $\Rightarrow$ Generation of the spacetime as a part of a configuration space.
- A natural geometry generated by transition amplitudes (hypothesis).
- New observables and phenomena in the time domain.
- ...