Double slit experiment in time domain from the TGD perspective

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Abstract

The temporal analog of the double slit experiment carried out by a research team led by Riccardo Sapienza has gained a lot of attention. The experiment is a generalization of the regular double slit experiment to the time domain. The results of the experiment challenge the existing views of quantum physics and it is interesting to see whether the zero energy ontology (ZEO) to which TGD inspired quantum measurement theory is based, could provide new insights about the experiment.

The basic outcome of the considerations is that at least at the level of principle it is possible to determine the classical em fields in the geometric past after a pair of "big" state functions, which are the TGD counterparts of ordinary state function reductions and change the arrow of geometric time. Violations of classical causality based on finite signal velocity would serve as a support for the ZEO.

Contents

1 Introduction

The temporal analog of the double slit experiment carried out by a research team led by Riccardo Sapienza [D1] has gained a lot of attention. The experiment is a generalization of the regular double slit experiment to the time domain (rebrand.ly/tmbz3gu).

I am grateful to Tuomas Sorakivi for turning my attention to a Youtube video "Light Can Interfere in Time as well as Space" by Ben Milles (rebrand.ly/zz3jq2a). The discussions in our

Zoom group about the experiment inspired this article and led to an idea that the testing of the basic predictions of zero energy ontology might be possible.

There are also popular articles about the experiment in Live Science (`rebrand.ly/o0ojyya`) and in Quantum Insider (`rebrand.ly/y3k24gl`).

The following is the abstract of the research article [D1]:

"Double-slit experiments—where a wave is transmitted through a thin double aperture in space—have confirmed the wave–particle duality of quantum objects, such as single photons, electrons, neutrons, atoms and large molecules. Yet, the temporal counterpart of Young's double-slit experiment—a wave interacting with a double temporal modulation of an interface—remains elusive. Here we report such a time-domain version of the classic Young's double-slit experiment: a beam of light twice gated in time produces an interference in the frequency spectrum.

The 'time slits', narrow enough to produce diffraction at optical frequencies, are generated from the optical excitation of a thin film of indium tin oxide near its epsilon-near-zero point. The separation between time slits determines the period of oscillations in the frequency spectrum, whereas the decay of fringe visibility in frequency reveals the shape of the time slits.

Surprisingly, many more oscillations are visible than expected from existing theory, implying a rise time that approaches an optical cycle. This result enables the further exploration of time-varying physics, towards the spectral synthesis of waves and applications such as signal processing and neuromorphic computation."

The temporal analog of double slit experiments are expected to have many technological applications:

"The observation of temporal Young's double-slit diffraction paves the way for the optical realizations of time-varying metamaterials, promising enhanced wave functionalities such as non-reciprocity, new forms of gain, time reversal and optical Floquet topology. The visibility of oscillations can be used to measure the phase coherence of the wave interacting with it, similar to wave–matter interferometers. Double-slit time diffraction could be extended to other wave domains, for example, matter waves, optomechanics and acoustics, electronics and spintronics, with applications for pulse shaping, signal processing and neuromorphic computation."

1.1 Double slit experiment in spatial domain

One can look at the description of the situation in Maxwell's classical theory first. One has two slits at the first screen characterized by their distance and their widths. They parameterize the diffraction pattern at the second screen. The beam can be assumed to be monochromatic and normal to the screen.

Formally one can say that the transparency of the screen containing the slits is varying. It vanishes outside the slits and is maximal at the slits. The transparency of the screen depends on position. The modelling based on Maxwell's equations assumes incoming beam of light, say plane wave in definite direction and presence of the first screen described in terms of transparency. One can solve Maxwell's equations and predict the diffraction pattern.

One can study the spatial interference pattern at the second screen or equivalently, its Fourier transform with respect to a coordinate parallel to the screen and in the direction vertical to the parallel slits. One obtains a diffraction pattern also in the space of wave vectors (photon momenta in the quantum situation). The dominating peak is associated with the wave vector associated with the incoming beam.

In the diffraction, the normal component of the wave vector is conserved but the tangential component can change. This gives rise to dispersion with respect to the tangential component of the wave vector. At single photon level one can say that the slit scatters the incoming photons to various directions.

Hitherto everything has been purely classical. What makes the phenomenon so remarkable is that the double slit diffraction patterns appear also when single photons are used. This takes place also for other particles. The classical view of a particle would predict two peaks behind the slits.

1.2 Double slit experiment in time domain

What happens in the temporal double slit experiment is very similar to what happens in the regular case. One cannot directly measure the temporal patterns of the reflected wave. One can however measure the intensity as a function of frequency characterized by the Fourier transform of the reflected electromagnetic field. If one is also able to determine the phases of the Fourier components theoretically, one could also estimate the fields at the level of space-time, even those before the first pump pulse.

The frequency distribution is qualitatively similar to that for the wave vector distribution in the regular double slit experiment. Slit becomes pulse, slit width becomes the duration of pulse, and the distance between slits becomes the interval between pulses.

The effect is stronger than expected for short pulse durations approaching the optical cycle $T = 1/f$ where f is the frequency of the incoming laser beams. The proposal is that what matters is the time scale τ for the change from transparency to reflectivity lasting as the duration of the pulse. One has $\tau = 2.3$ fs is roughly one half of the period $T = 1/f = 4.4$ fs of the period of incoming laser beam. The duration between pulses is .8 ps.

During period τ the dispersion of the chromatic beam to frequencies around the peak frequency would take place and could be understood mathematically as following from the time dependence of the refractive index (or reflection coefficient).

The frequency dispersion occurs already for a single pulse and gives rise to a single maximum as in the case of the ordinary single slit experiment. For two pulses a diffraction pattern in the frequency domain resembling that of the double slit experiment is observed. The shorter the duration of the pulse is and the shorter the time interval between slits is, the more pronounced the diffraction pattern is.

Maxwell's equations in the presence of the screen with time dependent refractive index describes the situation classically in the first approximation. Time dependent refractive index characterizes the screen. Refractive index does not change during the period between pump pulses but changes during the period τ to a constant value preserved during the pump pulse and after that returns to its original value. The interpretation would be that pump pulse feeds to the system energy needed to keep the value of the refractive index constant allowing reflection. One can say that during the pulse the system is not closed.

In the Maxwellian view, the reflected fields propagate with a light velocity. This gives rise to classical causality. The temporal field pattern of the reflected wave deducible by the inverse Fourier transform from its frequency pattern should vanish before the first pulse. But is this really the case? Time reversal is mentioned in the abstract of the article: is there evidence that this is actually not the case?

2 TGD view of the double-slit experiment in temporal domain

Consider next the TGD [L6] based quantum view of the situation.

2.1 Basic incredients

There are several new ingredients involved.

1. TGD leads to a new view of space-time [L11]. Point-like particles are replaced by 3-surfaces in $H = M^4 \times CP_2$ and their orbits determine space-time regions. The regions of space-time surface obey almost deterministic holography, being analogous to Bohr orbits.

2. Holography forces zero energy ontology (ZEO) [L2, L1, L7, L5] replacing the standard ontology of quantum theory and solving the basic paradox of the quantum measurement theory. ZEO also leads to a new view of what occurs in state function reductions (SFRs).

3. Number theoretic view of TGD predicts a hierarchy of effective Planck constants $h_{eff} = nh_0$ [K1, K2, K3, K4] characterizing phases of ordinary matter behaving in many respects like dark matter. They allow long length scale quantum coherence. In the recent case, laser beams could have $h_{eff} > h$.

4. Momentum position duality is generalized to $M^8 - H$ duality [L3, L4, L9], which states that the M^8 picture providing algebraic and number theoretic view of physics is complementary to the geometric view of physics.

This framework could allow totally new insights of the double slit experiment in the time domain.

2.2 ZEO briefly

I have explained ZEO so many times that I will give only a very brief sketch.

1. In ZEO, quantum states are superpositions of classical time evolutions obeying almost, but not quite(!) exact holography [L10, L11, L8]. These time evolutions correspond to space-time surfaces analogous to Bohr orbits. These space-time surfaces are within a causal diamond (CD) and zero energy states are pairs of 3-D states as analogs of ordinary 3-D quantum states at the opposite boundaries of the CD identifiable as superpositions of 3-surfaces.

2. There are two kinds of state function reductions (SFRs) [K5] [L2, L5, **?**]. "Small" SFRs (SSFRs) preserve the arrow of time, and their sequence is the counterpart for repeated quantum measurements which do not affect the system at all (Zeno effect). SSFRs do not affect the passive boundary nor 3-D states at it. SSFRs affect the states at the active boundary of CD and in a statistical sense shift it farther away from the passive boundary. This shifting corresponds to the increase of the geometric time identified as the distance between the tips of CD. Geometric time therefore correlates with the subjective time identified as the sequence of SSFRs.

3. In "big" SFRs (BSFRs), which are counterparts of ordinary SFRs the arrow of time changes and the roles of active and passive boundaries of CD are changed. SSFRs correspond to a sequence of measurements of fixed observables. The states at the passive boundary are eigenstates for a subset of these observables and are not affected in SSFRs. When the set of measured observables changes by external perturbation, BSFR must occur and change the arrow of time temporarily. Quantum tunnelling would correspond to a temporary change of the arrow of time caused by two BSFRs.

Could ZEO make it possible to say something interesting about the time slit experiments?

1. In Maxwellian view the reflected fields propagate with light velocity. This gives rise to classical causality. In the Maxwellian picture, the temporal field pattern of the reflected wave, possibly deducible by inverse Fourier transform from its Fourier transform, should vanish before the first pulse. Is this really the case? Can this be tested? Time reversal is mentioned in the abstract of the article, is there evidence for the occurrence of a temporary time reversal.

2. Could the pump pulse induce BSFR and a temporary time reversal? The end of the pulse would induce a second BSFR and bring back the original arrow of time. Since SFRs replace the superposition of classical space-time surfaces (classical time evolutions and therefore field patterns) with a new one, the pair of BSFRs would change the classical field patterns also in the geometric past.

   Could the classical field patterns be deduced from the frequency spectrum of reflected waves? If it is possible to estimate the phases of the Fourier components theoretically, it is in principle to estimate the classical spatiotemporal field patterns in the geometric past.

   If they violate classical causality, i.e. are non-vanishing before the first pump pulse, one can conclude that the experiment provides a strong support for ZEO. Quite generally, one might someday be able to measure what happens to the geometric past in BSFR pairs.

2.3 Can one determine the classical fields in the geometric by measuring the Fourier transform?

In principle, there are good hopes that in the TGD Universe it might be possible to deduce from the frequency spectrum of the reflected light the spatiotemporal behavior of the reflected wave in the geometric past and therefore test ZEO. There are several reasons for why this should be the case.

1. Classical fields are geometrized in TGD. For a single space-time surface the classical fields are determined completely by the surface itself as induced fields. This simplifies dramatically the mathematical picture.

2. Topological quantization means that Maxwellian classical fields decompose to topological field quanta, which or at least their M^4 projections have a finite size. One obtains a variety of field quanta. Massless extremals (MEs) are highly analogous to laser beams and represent precisely targeted propagation in which the pulses consisting of Fourier components with only a single direction of wave vector in the direction of ME preserve their shape.

   The pulse beam, incoming laser beam and reflected light beam(s) could be modelled in terms of MEs. The reflected beam could correspond to a ME representing a superposition of analogs of parallel plane waves with different frequencies. Monochromatic ME becomes multichromatic ME in the reflection. One could say that the frequency dispersion represents new physics predicted by TGD.

3. Holography makes it possible to deduce a given space-time surface from a 3-D holographic data, basically a set of 3-surfaces. There is no need to know the 4-D tangent spaces at the 3-surfaces.

   There is however a small violation of determinism for the holography, which in fact forces ZEO. At the space-time level this corresponds to the fact that space-time surfaces as minimal surfaces are not completely fixed by holographic data, which is analogous to frames spanning soap films.

4. Complexified M^8 is an analog of 8-D momentum space and a given 4-surface in M^8 is determined by roots of a polynomials, which correspond to mass shells $H^3 \subset M^4 \subset M^8 = M^4 \times E^4$. The 4-surface $Y^4 \subset M^8$ must go through 3-surfaces at these mass shells defining the holographic data.

   The condition that the normal space of 4-surface $Y^4 \subset M^8$ going through these mass shells is associative allows us to realize M^8 holography almost uniquely.

5. One can also apply $M^8 - H$ duality, which is analogous to momentum position duality of wave mechanics. $M^8 - H$ duality maps $Y^4 \subset M^8$ to a space-time surface $X^4 \subset H = M^4 \times CP_2$ and induces holography at the level of H. For space-time surfaces, holography means a generalization of holomorphy from 2-D to a 4-D situation.

   In particular, mass shells are mapped by the inversion mapping M^4 momentum value at mass shell to a light-cone proper time $a = constant$ hyperboloid in $M^4 \subset H$. The momentum components are in general algebraic integers and therefore complex. Therefore one must take the real part of the image by inversion. One has $p^k \rightarrow Re[h_{eff}p^k/p_lp^l]$ [L9].

   This works when mass squared $p^lkp_l = m^2$ is nonvanishing. Photons are however massless. In this case the inversion is ill-defined. In the massless case polynomials determine energy shells in M^4. In this case, the associative holography is based on energy shells. The inversion must map light-cones boundaries to light-cone boundaries. Complex algebraic integer valued energy E is mapped to $t = Re[h_{eff}/E]$.

6. 3-D holographic data at the mass shells in H^3, and in the special case at light-cone boundaries for massless photons, codes for the frequency spectrum and this in principle determines the classical fields in X^4 by $M^8 - H$ duality.

   Associative holography and $M^8 - H$ duality would make it possible to calculate the classical fields in the geometric past before the first pump pulse and test ZEO by comparing them with those predicted by the classical causality.

7. Number theoretical view brings in also the notion of finite measurement resolution, necessary for number theoretical universality needed when p-adic physics is introduced as a correlate for cognition. This simplifies further the situation.

   Finite measurement resolution requires a number theoretical discretization of mass shells, which is unique. Allowed 4-momenta components, which are algebraic integers for an algebraic extension determined by the polynomial P whose roots define mass shells in turn determining Y^4. The momentum unit corresponds to the size scale of the causal diamond (CD).

   The physical states expressible as bound states of fundamental fermions and antifermions are Galois singlets for which momentum components are ordinary integers.

   An interesting possibility is that, in a finite measurement resolution determined by the polynomial P, all space-time surfaces in the superposition defining a given zero energy state have the same number theoretic discretization. Finite measurement resolution would make the quantum states effectively classical apart from the non-determinism associated with the holography!

In principle, this picture would allow us to determine the classical fields in the geometric past from the frequency spectrum and to check whether they are consistent with the classical causality. The appearance of the reflected wave is already before the first pulse could be regarded as an empirical support, if not a proof for the ZEO!

Of course, in reality the space-time of standard model is determined as an approximation by replacing the space-time visualizable as topologically extremely complex many-sheeted structure with its M^4 projection such that the sums of the induced fields at various sheets define standard model gauge fields and gravitational field as the sum of the deviations of the induce metric from the Minkowski metric.

REFERENCES

Condensed Matter Physics

[D1] Tirole R et al. Double-slit time diffraction at optical frequencies. *Nature Physics*, 19:999–1002, 2023. Available at: https://www.nature.com/articles/s41567-023-01993-w.

Books related to TGD

[K1] Pitkänen M. Criticality and dark matter: part I. In *Hyper-finite Factors and Dark Matter Hierarchy: Part I.* Available at: https:/tgdtheory.fi/pdfpool/qcritdark1.pdf, 2019.

[K2] Pitkänen M. Criticality and dark matter: part II. In *Hyper-finite Factors and Dark Matter Hierarchy: Part I.* Available at: https:/tgdtheory.fi/pdfpool/qcritdark2.pdf, 2019.

[K3] Pitkänen M. Criticality and dark matter: part III. In *Hyper-finite Factors and Dark Matter Hierarchy: Part I.* Available at: https:/tgdtheory.fi/pdfpool/qcritdark3.pdf, 2019.

[K4] Pitkänen M. Criticality and dark matter: part IV. In *Hyper-finite Factors and Dark Matter Hierarchy: Part I.* Available at: https:/tgdtheory.fi/pdfpool/qcritdark4.pdf, 2019.

[K5] Pitkänen M. Zero Energy Ontology. In *Towards M-Matrix: part I.* Available at: https:/tgdtheory.fi/pdfpool/ZEO.pdf, 2021.

Articles about TGD

[L1] Pitkänen M. New insights about quantum criticality for twistor lift inspired by analogy with ordinary criticality. Available at: https:/tgdtheory.fi/public_html/articles/zeocriticality.pdf., 2018.

[L2] Pitkänen M. Some comments related to Zero Energy Ontology (ZEO). Available at: https:/tgdtheory.fi/public_html/articles/zeoquestions.pdf., 2019.

[L3] Pitkänen M. A critical re-examination of $M^8 - H$ duality hypothesis: part I. Available at: https:/tgdtheory.fi/public_html/articles/M8H1.pdf., 2020.

[L4] Pitkänen M. A critical re-examination of $M^8 - H$ duality hypothesis: part II. Available at: https:/tgdtheory.fi/public_html/articles/M8H2.pdf., 2020.

[L5] Pitkänen M. Some questions concerning zero energy ontology. https://tgdtheory.fi/public_html/articles/zeonew.pdf., 2021.

[L6] Pitkänen M. TGD as it is towards the end of 2021. https://tgdtheory.fi/public_html/articles/TGD2021.pdf., 2021.

[L7] Pitkänen M. About the number theoretic aspects of zero energy ontology. https://tgdtheory.fi/public_html/articles/ZEOnumber.pdf., 2022.

[L8] Pitkänen M. About the TGD based views of family replication phenomenon and color confinement. https://tgdtheory.fi/public_html/articles/emuanomaly.pdf., 2023.

[L9] Pitkänen M. New findings related to the number theoretical view of TGD. https://tgdtheory.fi/public_html/articles/M8Hagain.pdf., 2023.

[L10] Pitkänen M. New result about causal diamonds from the TGD view point of view. https://tgdtheory.fi/public_html/articles/CDconformal.pdf., 2023.

[L11] Pitkänen M. Reduction of standard model structure to CP_2 geometry and other key ideas of TGD. https://tgdtheory.fi/public_html/articles/cp2etc.pdf., 2023.