

# THE SIGNIFICANCE OF THE PROPER FRAME OF THE PHOTON FOR THE EPISTEMOLOGY OF QUANTUM MECHANICS

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A philosophical analysis of the proper frame of the photon shows that the Minkowskian spacetime of Special Relativity can support a zero-dimensional non-local field. This non-local field allows an understanding of some quantum physical events such as quantization, the measurement problem and entanglement from a “Minkowskian viewpoint”. It also helps explain the mysterious results of such experiments as the delayed choice quantum eraser. Consequences are that light and gravity waves might in fact not carry energy per se but only the information that defines it. According to this view, all particles exhibiting quantum properties must include a “component” moving at light speed. Those concepts show more common ground between Special Relativity and Quantum Mechanics than previously thought, although a true relation cannot be claimed at this point.

Une analyse philosophique du système de référence propre au photon démontre que l'espace-temps de Minkowski de la Relativité Spéciale définit un champ non local à zéro dimension. Ce champ semble expliquer certains phénomènes quantiques tel que le fait que la lumière est quantique, le problème de la mesure quantique et le problème de l'intrication quantique. Il explique aussi certains résultats expérimentaux comme ceux de la gomme quantique à choix retardé. Certaines conséquences de cette approche sont que les ondes lumineuses et gravitationnelles, en fait, ne transportent pas d'énergie mais seulement l'information qui définit cette énergie et que les particules qui ont des propriétés quantiques doivent inclure un «constituant» qui se déplace à la vitesse de la lumière. Ces concepts montrent que la Relativité Spéciale et la Mécanique Quantique sont plus proches qu'on ne pouvait penser, mais une vraie relation reste encore à démontrer.

Key words: photon, graviton, special relativity, non-relativistic quantum mechanics, relativistic quantum mechanics, blockworld, entanglement, quantum eraser, non-locality

## INTRODUCTION:

The epistemology of electromagnetic radiations is that they travel as waves (electromagnetic waves, EMW) at the speed of light and manifest as basic discrete bundles of energy which are particles of light called “photons” (1). Depending on the experimental apparatus, those radiations will display preferentially their wave-like or particle-like nature, according to constructs the body of which forms the theory of non-relativistic quantum mechanics (QM).

Paradoxes arise in two-slit type experiments where the wave-like nature of light is demonstrated by the formation of an interference pattern (Fig. 1). Even when photons are emitted one at a time, the distribution appears on the receptor screen as an interference pattern, against the expectations of classical physics. This leads to a puzzling epistemology where a photon particle is considered to go through two separate slits at the same time and interfere with itself (2).

Non-relativistic Quantum Mechanics (QM) is the study of the microscopic world of particles where many properties (such as energy) are usually found only in certain elementary amounts (called quantum or quanta) or multiple integers of those amounts. As mentioned, the energy quantum of light (or particle of light) is called a photon (3).

QM was originally created as a recipe for calculating the expectation values of observables measured by macroscopic measuring instruments (4). Mathematically, it represents the properties of quantum systems as subspaces in a linear vector space over the complex numbers called Hilbert space. This abstract projective geometry allows a physical event to be represented by a superposition of state vectors. Each state vector reflects the probability of finding the physical event in the state under consideration, therefore expressing a specific observable value.

When an observation is made, this superposition collapses to a single observable value which is the measurement. This physical event is alternatively called “state vector reduction”, “collapse of the wavefunction” and is more generally referred to as “the measurement problem”.

QM also includes correlations via “entangled states” whereas two (or more) particles are said to be entangled if they exhibit an instantaneous correlation of at least one of their properties (such as spin) no matter how far apart they may happen to be. This puzzling effect is also called non-locality.

Despite its impressive achievements of explaining previously puzzling physical events (from the existence of spectral lines and the stability of atoms to superconductivity and superfluidity), many physicists feel that the mathematical formalism of QM doesn't provide a clear picture of reality. Others believe that “... the unitary evolving quantum state completely describes actual reality, with the alarming implication that practically all quantum alternatives must always continue to coexist (in superposition)” (5).

QM especially fails to explain why there is such a thing as the quantum (6). It also does not explain the “measurement problem” nor does it explain “entanglement” (both previously mentioned).

Special Relativity (SR) is based on two postulates: The first one is that the laws of physics are the same for observers in all inertial reference frames. No one frame is preferred over any other. The second postulate is that the speed of light in the vacuum has the same value  $c$  in all directions and in all inertial reference frames (7). The apparent length contraction along the line of motion, the slowing of time with increasing speed and the trans-temporality of objects or particles (the blockworld concept), are ultimately consequences of the postulates of SR.

For Einstein, SR implies the assumption of locality. This concept requires “... that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past ...” (8). Einstein fought vigorously against the concept of entanglement and its implication of non-locality. He called it a “spooky action at a distance” (9). The debate was so intense that it has been an accepted fact ever since that SR cannot support non-locality. This is probably best expressed by Dirac (10) in his development of relativistic QM (RQM). He writes: “Let us see how the basic ideas of quantum theory can be adapted to the relativistic point of view that the four dimensions of spacetime should be treated on the same footing”. He then warns: “However, the general concept of an observable does not fit in, since an observable may involve physical things at widely separated points at one instant in time”.

This paper explores whether or not SR has been underestimated by Einstein and could in fact predict non-local effects and shed some light on some of the quantum physical events not explained by QM (namely the existence of the quantum, the measurement problem and entanglement).

#### THE BLOCKWORLD CONCEPT AND TRANS-TEMPORALITY:

In the blockworld concept, the past, present and future are all equally real. This is derived from the principle of the relativity of simultaneity per SR: for example, astronauts in relative motion “share realness” in the past or future of each other. The past and the future therefore must be as real as the present (11) and particles (and objects) are therefore trans-temporal, meaning that a given particle exists at each instant in time. Blockworld is fundamentally non-dynamical and, according to its proponents, a deeper and truer representation of reality than dynamical models such as QM (12).

#### THE PROPER FRAME OF THE PHOTON AND MINKOWSKIAN NULL-CONNECTIVITY AND NON-LOCALITY:

For the purpose of this paper, gravity will be considered to be uniform and negligible. The world line of a photon can be regarded as one-dimensional, even though it evolves in spacetime (spacetime will be considered to be the Minkowskian four-manifold,  $M_4$ , and called  $\{S\}$ ;  $\{S\}$  will refer alternatively to spacetime as a whole and to any inertial reference frame therein). In figure 2, if an observer was able to take an instantaneous snapshot of the photon as it passes at point **A**, this would show no distance and no time

intervals and record an instantaneous speed of magnitude  $c$ . This could be repeated indefinitely along the world line. As the proper frame of the photon measures no distance in the direction of motion, all those points can be considered collapsed to the same one point, as viewed from within the system. Similarly, as time appears frozen in the photon's proper frame with respect to observations outside the system for all observers, time measurements would also be recorded as zero. Essentially, the photon's proper frame compels the photon to appear zero-dimensional to all observers. This would remain true whether this observer uses a Galilean or an Euclidean 4-manifold (respectively G4 and E4) as reference frame. The photon represents the energy of its electromagnetic wave (EMW) and therefore those concepts apply to the EMW itself.

M4 is trivially used for SR. This reference frame embeds the Lorentz transformations in the fabric of spacetime. A primed inertial reference frame with a velocity  $\mathbf{v}$  relative to a non primed initial inertial reference frame, sees its time and space axis converge from their respective vertical and horizontal positions when  $\mathbf{v} = 0$ , to a 45 degrees line when  $\mathbf{v} = c$ . In the traditional Minkowski diagram, this line represents the light cone of EMW in particular or light speed waves (LSW) in general. The Lorentz invariant interval between two events is considered to be

$$ds^2 = c^2 dt^2 - dx^2 - dy^2 - dz^2$$

(where  $t$  represents the time dimension and  $x, y, z$ , the three space dimensions). If  $ds^2$  is positive, the two events are said to be time-like separated and there exists an inertial reference frame in which they have the same space coordinates and differ only in time. If  $ds^2$  is negative, the two events are said to be space-like separated and there exists an inertial reference frame in which they are simultaneous in time and differ only in space coordinates. If  $ds^2$  is zero, the two events are said to be light-like (13, 14). Events on the light cone are said to have no time or space separation (15). For this reason, the light cone is also called the *null cone*. *The null cone therefore essentially behaves as a zero-dimensional space and corresponds to the zero-dimensional proper frame of the photon previously encountered for E4 and G4.*

It must be noted that the null interval of Minkowskian space cannot be assimilated with Euclidean (or Galilean) distance zero (16). What is zero-dimensional in E4 or G4 is the proper frame of the photon itself, as seen by an observer residing in either of those reference frames. The spacetimes of E4 or G4 are never themselves zero-dimensional.

Trivially, one can construct a "mesh" of null cones covering the whole of M4. This "mesh" behaves as a zero-dimensional space from the viewpoint of which any two events would be observed as coincident (simultaneous and at the same location), even though they are distinct when observed from outside the null cone. Those properties are essentially non-local and the zero-dimensional space can be considered to be a non-local field encompassing M4. We will name this non-local field  $\{Z\}$ . *In other words, as any two events in M4 can be joined by null path segments, along which zero proper time lapses, the whole of M4 must be considered non-locally connected.  $\{Z\}$  is analogous to the focal point of an optical convex lens where all the images going through the lens converge to a single point (i.e., the 3-dimensional lens condenses the 2-dimensional images to one point).*

For an observer located on the initial inertial reference frame, two points on the null cone could be called “null-connected”, but for an observer located on the null cone itself, this “null-connectivity” becomes a “non-locality” for the reasons mentioned above. It must be immediately noted that this “Minkowskian non-locality” cannot be assimilated with the non-locality of QM. QM mathematics and the non-locality they imply reside in complex space and not in M4. Moreover, QM non-locality applies to probabilistic expectations over the outcomes of large number of trials of experiments usually analyzed within G4.

What would be  $\{Z\}$ 's mathematical properties? We must keep in mind that this Minkowskian zero-dimensional space is not equivalent to its Euclidean or Galilean counterparts. For simplicity, we will consider a line  $L$  of the null cone (a one-dimensional manifold). For  $\{Z\}$ , all the points of  $L$  are considered collapsed to a single point. As all the dimensions are to be considered on an equal footing, if a property  $P$  takes a value  $P_i$  (real or imaginary) at any point  $x_i$  ( $x \in L$ ), then the value of  $P$  within  $\{Z\}$  would be

$$P_{\{Z\}} = \sum P_i$$

If  $P$  is a function of  $x$  ( $x \in L$ ), so that  $P_i = f(x_i)$ , then we would have

$$P_{\{Z\}} = \int f(x) dx$$

As the gradient of  $f(x)$  is necessarily a null vector in  $\{Z\}$ ,  $f(x)$  must be a constant function with respect to  $x$  if it exists within  $\{Z\}$ .

Trivially,  $\{Z\}$  remains unaffected by a change of the scale of  $\{S\}$  (M4), as the null cone would simply change in a proportional fashion. Similarly,  $\{Z\}$  would remain unaffected if the number of dimensions of the Minkowskian manifold is changed from four to any arbitrary integer  $n$ . The mathematical properties of  $\{Z\}$  would also remain valid under those changes.

Those concepts would remain true for any wave moving at light speed, and therefore would apply to gravitational waves as well (both gravitational waves and EMW being light speed waves, LSW). It must also be noted that, by definition,  $\{Z\}$  being non-local and zero-dimensional, it is non-deterministic in essence (in the sense that an initial condition does not yield a definite time evolution).

#### ABOUT ENERGY ON THE NULL CONE:

In  $\{S\}$ , the total energy of a particle is the time component of the four-momentum which, itself, is a time-like four-vector. According to Pathria (17), its norm is

$$p_i p_i = m_0^2 c^2,$$

where  $m_0$  is the rest mass of the particle and  $c$  the speed of light. The spatial and temporal components of the four-vector always remain distinct and are

$$[\gamma m_0 \mathbf{v}, \gamma i m_0 c],$$

where  $m_0$  is again the rest mass of the particle,  $v$  is its relative speed,  $c$  the speed of light,  $i = (-1)^{1/2}$  and  $\gamma = (1 - v^2/c^2)^{-1/2}$ . This can be rewritten

$$[\mathbf{p}, i E/c],$$

where  $\mathbf{p}$  is the three-dimensional momentum of the particle and  $E$  its total energy. In the case of a photon,  $p$  and  $E$  are kept finite and we have  $m_0 \rightarrow 0$  and  $v \rightarrow c$ . The four-momentum takes the form

$$(p_i) = (\mathbf{p}, ip); p_i p_i = 0.$$

Pathria writes “This is a *null* vector, ‘tangential’ to the trajectory of the (nonmaterial) particle, that lies wholly on the light cone”.  $E$  is therefore a scalar function depending only on the relative speed between inertial reference frames (the vectorial component of the four-momentum is the three-momentum). From the equations,  $E$  is a constant function with respect to time and location for any given inertial reference frame and its gradient would be a null vector (however,  $E$  is not Lorentz invariant and therefore would vary from one inertial reference frame to the other).

We can imagine  $\{Z\}$  to be the focal point of a five-dimensional “convex” lens which projects the four-dimensional null cone to this single point. Just like its three-dimensional counterpart, the five-dimensional lens also concentrates all the energy present on the null cone into this point ( $\{Z\}$ ) in a cumulative fashion. We can do this because, trivially, for a given system, the total energy content of all the individual objects at a given moment in time (space-like events) is the sum of the individual energies (i.e., energy is cumulative across space). As all dimensions are on an equal footing in M4, the energy of a system of time-like events (at same space coordinates) must also be additive (i.e., energy is cumulative across time). Therefore, if two distinct points A and B (with respect to the initial inertial reference frame of the null cone) have respectively energies  $E_A$  and  $E_B$ , the resulting energy for  $\{Z\}$  will be  $E_A + E_B$ .

We immediately see that this gives us a problem if the photon has a trans-temporal existence as implied by blockworld and SR. In this picture, the photon exists at every point of its world line and, on a line, one can always position a point between two other points (at least down to the Planck length). As the photon’s energy,  $E$ , is present at each of those points (say  $\mathbf{x}$ ),  $E$  would be infinite (or near infinite) in  $\{Z\}$  (Fig. 3). The main problem, however, is that the total energy in  $\{Z\}$  is now dependent on the length of the world line of the photon. If the photon travels twice as far and exists at each point of its world line (each time with energy  $E$ ), the summation in  $\{Z\}$  gives twice the energy. We would therefore have an inertial reference frame where the photon builds energy as it progresses. This doesn’t fit our understanding of energy and represents a conundrum.

Let’s immediately note that the above considerations are valid only for light speed particles. Time-like particles and macroscopic objects, *per se*, do not exist in a non-local zero-dimensional space and are more complex. The concept of trans-temporality is derived from the relativity of simultaneity per SR and remains valid for those. There is no reason to believe that the concept of blockworld would not apply there.

How do we get out of this conundrum? We must come to the conclusion that an energy carrying particle cannot both have a trans-temporal existence and move at light speed. We must either admit that SR is wrong in its prediction of trans-temporality for light speed particles, or we must accept that there is no such thing as an energy carrying light speed particle (such as a photon) that can co-exist at every point of its world line.

The photon is the quantum of energy carried by an EMW. A possible resolution of the above conundrum is to consider that what is carried by the EMW is not the energy per se, but the *information* that defines that energy.

It will therefore be assumed that an *encoding process* activates a suitable EMW which will be postulated to exist in a latent state as part of the background vacuum. A *decoding process* manifests the energy when a suitable interaction or measurement occurs and concurrently terminates the wave. This manifestation is indistinguishable from what is conceived as a “particle” but the energy is carried by the EMW only as *information* (information will be taken here in its classical sense; it is not quantized information as understood by Bub (18)). We will also assume that the information carrying capacity of the EMW largely exceeds the amount of information being transmitted. The words “interaction” and “measurement” will be used interchangeably and will usually involve an exchange of energy.

The magnitudes of the energy, momentum and spin (as examples) and all other characteristics that describe the “particle” will be considered carried by the EMW as information. *As they exist within {Z} and as {Z} accepts only constant functions with respect to time and location for any given inertial reference frame (i.e. functions with a null gradient), those values must remain invariant or sum up to invariant values that will act as constants.* Those will be called *extrinsic constants*.

In this conceptual framework, the EMW itself has a real physical existence in the classical sense and is therefore different from the mathematical wavefunctions of QM which describe the probability of finding a physical system in a particular state (see later paragraph for similarities and differences with the de Broglie-Bohm approach to QM).

It can be postulated that the wave and the information it carries are intertwined. Distinct waves, each with a distinct set of information, may coexist and be superposed. The superposition principle of QM is therefore preserved. As each superposition can be described by a state vector in complex space, the mathematical formalism of QM remains unchanged by this scheme. However, those alternatives manifest as *one reality* and the uncomfortable concept of *superposed realities* is therefore avoided. As those considerations are valid for LSW, they would also apply to gravity.

#### ABOUT THE ONE-QUANTUM ELECTROMAGNETIC WAVE:

Let us imagine a point light source, **O**, emitting light isotropically within an arbitrary volume defined by the three spatial dimensions of M4. The emission of the light source is a (real) spherical electromagnetic wavefront (EMWF) (as we would obtain an interference pattern if we were to place a Thomas Young interferometer along any radius of the sphere defined by the wavefront). On a Minkowkian diagram (which sacrifices one of the spatial dimensions for the sake of visualization), the EMWF would be represented by a circle progressing along the null cone. If we were to decrease the strength of the source so that it only emits one quantum of light (photon) at a time, we would still get an interference pattern at the interferometer if we waited long enough. This would remain true no matter where we position this interferometer along any arbitrary radius of the

sphere defined by the EMWF. We could therefore conclude that the source is still emitting *a real spherical EMW in which is embedded the “photon’s” energy information.*

If we now imagine a sphere of radius  $\mathbf{r}$  lined up with photon detectors directed inward and centered on  $\mathbf{O}$ , the photon would be detected anywhere on the surface of the wavefront (as it reaches the detector sphere) in a random fashion (on the Minkowskian diagram this would be anywhere on the circle that represents the EMW on the null cone). This introduces a probabilistic component to the detection of the photon and our real EMW can be considered to also have a probabilistic element.  $\{Z\}$  projects to the whole EMWF with the photon’s energy information and this is why the wavefront is embedded with this information. However,  *$\{Z\}$  is itself only a zero-dimensional point and the photon can therefore only manifest as such* (in the absence of a down-conversion process). When a measurement or interaction occurs,  $\{Z\}$  compels the photon to manifest at only one point on the surface of the EMWF. In our model, *it is therefore the non-local field  $\{Z\}$  which introduces a probabilistic element to the EMW.* This is only evident when the energy of the wave is decreased to one quantum. This point-like manifestation of the photon, compelled by  $\{Z\}$ , will remain true no matter the number of dimensions in which the EMW may disperse. For example, if the EMW was dispersing as an hypersphere in four dimensions, the photon would still manifest as a single zero-dimensional point (again, in the absence of a down-conversion process).

If we consider our previous spherical “one-quantum” wavefront, the role of  $\{Z\}$  (in the manner in which the photon manifests) is clear. The wave is produced by a real source and propagates in real space (although within a Minkowskian three-manifold representation) and therefore should be considered real, even though it has a probabilistic component. The evolution of the EMW itself is deterministic but the manifestation of the photon is only probabilistic, as it appears randomly on the wavefront. Therefore, the photon itself cannot be described as traveling from  $\mathbf{O}$  to its point of detection (let’s say  $\mathbf{A}$ ). However, in the special case of a one-dimensional propagation of the EMW, the whole wavefront of the EMW reduces to a single point where the photon will necessarily manifest. In this case (and in this case only), the evolution of the photon will *give the appearance* of being deterministic. Here, the probabilistic role of  $\{Z\}$  has been relegated to the background (we will expand on those concepts as we discuss the measurement problem).

We have so far reviewed Minkowskian non-locality, the behavior of energy on the null cone and how all this affects the one-quantum EWM. Before trying to see if this new paradigm helps us understand some of the quantum physical events not explained by QM theory, we will define some operations on the extrinsic constants.

#### AN ATTEMPT TO SYSTEMATIZE QUANTUM OPERATIONS:

Two types of operations will be distinguished which will be called “A” and “B” operations. “Waves” will be considered to be real waves instead of mathematical QM waves, unless otherwise specified.

“A” operations concern the LSW itself and represents its classical behavior. The geometry of the wave can be manipulated by the use of mirrors, semitransparent mirrors, polarizing filters, slits, etc..., giving rise to the various physical events of optics. The wave can be divided and reconstituted as an interference pattern.

Trivially, an “A” operation does not affect the constants existing in  $\{Z\}$ . As long as the information carrying capacity of the EMW is large in comparison to the amount of information carried, dividing the wave through an “A” operation does not alter that information. The resulting secondary waves, which may all exist simultaneously (and therefore can be considered “superposed”), all carry the same information. When a suitable interaction occurs involving any one of the secondary waves, the information manifests and all waves terminate. Consequently, under this model, a superposition of multiple secondary waves trivially gives rise to only one manifestation.

Contrary to “A” operations, “B” operations actually alter the information carried by the EMW so as to divide the magnitudes of some of the extrinsic constants. An example of a “B” operation would be the division of a parent EMW into daughter waves by a down-conversion process. A “B” operation always compels an associated “A” operation (as, trivially, the transmission of such information would always need the support of a wave) but the converse is not true. As compelled by  $\{Z\}$ , the properties of the daughter waves must always sum up to the constant value of that same property in the parent wave (Fig. 4). Those properties can be any characteristic carried by the wave that would manifest as part of a “particle” (energy, momentum, spin, etc...).

For example, in figure 4, a parent EMW is down-converted by a non-linear crystal or by spontaneous parametric fluorescence (DC) into two equal daughter waves, each with the same amount of energy. From the point of view of  $\{Z\}$ , the parent wave never separates and the various properties of the daughter waves sum up to the respective values they had in the parent wave. Those daughter waves can therefore be considered “entangled”. Simultaneous measurements performed on the daughter waves will always give correlated results.

It is to be noted that  $\{Z\}$  is indifferent to the geometry that the waves may adopt in  $\{S\}$ . The energy of the daughter waves will always sum up to the initial energy of the parent wave no matter when the daughter waves are measured with respect to the time axis (Fig. 5). For example, in figure 5, the down-conversion system  $[\mathbf{o}, \mathbf{a}, \mathbf{b}]$  of figure 4 becomes the system  $[\mathbf{o}', \mathbf{a}', \mathbf{b}']$  through a rotation in  $\{S\}$ . While,  $[\mathbf{a}]$  and  $[\mathbf{b}]$  show correlated results to measurements in what will be considered the present,  $[\mathbf{a}']$  and  $[\mathbf{b}']$  show correlated results respectively in the future and the past of that present. *For  $\{Z\}$ , there always exists an inertial reference frame where the interactions of each daughter wave are simultaneous.*

Figure 6 schematizes a general “B” operation. This could represent, for example, an interaction between two light-speed waves of different natures (an EMW and a gravitational wave). This reduces to the special case of entangled down-conversion when one of the input waves ( $[\mathbf{a}]$ , for example) has zero energy and when the energies of the

resulting (output or daughter) waves are equal. Each wave exists in  $\{Z\}$  and  $\{Z\}$  is the same for each. It can be reasonably stated that, under those circumstances, the magnitudes of the respective properties of the same nature (such as energy) will add arithmetically so that their sum represents a constant in  $\{Z\}$ .  $\{Z\}$  compels the total magnitude of any property (such as energy) of the wave system  $[a, b, c, d]$  to remain constant across the interaction “**I**” (across time, for any given inertial reference frame). *The necessity for the total energy of such a system to remain constant across an interaction suggests that the non-local field  $\{Z\}$  may play a role in the genesis of the energy’s conservation laws.* Those concepts may also be useful for an analysis of such an experiment as the Compton Effect (see later paragraph about the Compton Effect).

While the above discussion about A and B operations may appear to simply be a reformulation of the wave/particle duality arguments, they are helpful for a systematization of what happens in various experiments that will be discussed in later paragraphs (the delayed choice quantum eraser experiment and the Compton scattering experiment, for example). Moreover, “B” operations are wave-like and embed zero-dimensional non-locality. They cannot be considered equivalent to what is generally understood by a “particle”. The A/B operations duality is more appropriately described as a local/non-local duality.

Let us now see if this model can shed some light on the quantization issue, the measurement problem and entanglement.

#### THE QUANTIZATION OF LIGHT AND GRAVITY:

For a LSW, on the null cone (of M4) and for any given inertial reference frame, energy is therefore an extrinsic constant existing in  $\{Z\}$  as information and cannot vary (with respect to time and location, as previously discussed). Accordingly, in the case of EMW, there exists a baseline wave that carries this unchanging amount of energy that could be considered “elementary” and called a quantum. The only way to increase the total energy of a light beam is to multiply this elementary amount by adding similar baseline waves. The total energy obtained must therefore be an integer multiple of the “elementary” energy associated with a single wave. *The fact that a LSW exists both in  $\{Z\}$  and  $\{S\}$  obliges it to be quantized in  $\{S\}$ . The existence of the non-local field  $\{Z\}$  compels the quantization of light. As gravity moves at light speed, it would also be expected to be quantized.*

#### THE MEASUREMENT PROBLEM:

Greene writes “... According to standard quantum mechanics, when we perform a measurement and find a particle to be here, we cause its probability wave to change: the previous range of potential outcomes is reduced to the one actual result our measurement finds ...” He continues “... the measurement causes the probability wave to *collapse* ... the collapse happens instantaneously across the whole universe ...” (19). This physical event of instantaneous collapse of the probability wave is referred to as “the measurement problem”.

While QM mathematics occur in complex space, a physical counterpart can be constructed in  $\{S\}$  (M4) using our previous example of a spherical EMWF. We will here simplify the example by using a spatial two-dimensional propagation of the EMW. The same point source  $\mathbf{O}$  (located at the origin of a Cartesian coordinates “ $\mathbf{x}, \mathbf{y}$ ”) emits wavefronts at regular time intervals which are now circular, each with an energy of one quantum. The photon is detected randomly anywhere on the circular wavefront, as compelled by  $\{Z\}$ , for example at a point  $\mathbf{A}$  which is arbitrary (Fig. 7). In this situation, we have a measurement problem, analogous to the one of QM, which is embodied by the following question: How does the probability of finding the photon anywhere else immediately drop to zero when the photon is detected and how does the wave located at the antipodal location (for example) instantly “know” that the photon has manifested? In our current representation the answer is straightforward. All the points of the EMW are non-locally connected through the zero-dimensional space  $\{Z\}$ . With the manifestation of the photon, the EMW ceases to exist in  $\{Z\}$  and therefore everywhere  $\{Z\}$  projects. The EMW (including its real and probabilistic components) immediately terminates. The effects of  $\{Z\}$  such as compelling the use of a probabilistic approach and non-locally terminating the EMW can be considered non-deterministic.

We could also use a different approach to calculate the probability of the photon manifesting at  $\mathbf{A}$ . Instead of considering the deterministic evolution of a wavefront and then the probabilistic manifestation of the photon somewhere on that wavefront, we could posit that the probability of finding the photon at  $\mathbf{A}$  is the result of the linear deterministic evolution of a probability function (with respect to the coordinates  $\mathbf{x}, \mathbf{y}$ ) along the radius  $\mathbf{OA}$ . By appropriately choosing the probability function, we would arrive at equivalent results. However, the role of the non-local field  $\{Z\}$  is no longer apparent in this approach. It is  $\{Z\}$  that compels the use of a *probabilistic* function in the first place and it is  $\{Z\}$  that drops the probability of finding the photon anywhere else to zero, once it has manifested. But the mathematics of the probability function do not incorporate the role of  $\{Z\}$  when the manifestation of the photon occurs. By using a deterministic evolution, some of the non-deterministic effects of  $\{Z\}$  are concealed in the background. By analogy, we could hypothesize that the (complex) QM non-local field has similar non-deterministic properties as  $\{Z\}$  in the facts that it compels the use of a *probabilistic* wavefunction (when square integrated and normalized) to describe the chance of finding a particle at a certain location (or in a certain state) and that it terminates this probability once a manifestation (location or state) has occurred. Besides those two properties, the QM non-local field can be considered completely different from, and unrelated to,  $\{Z\}$ .

Following the same reasoning, by analogy, it can be seen that the deterministic evolution of the QM wavefunction in complex space relegates the existence of the complex non-local field to the background. While the mathematics of the wavefunction imply the existence of a non-local field, its deterministic evolution necessarily does not incorporate some of the field’s non-deterministic effects.

#### ENTANGLEMENT:

Entanglement is a property thought to be quintessential to QM where two correlated particles remain connected no matter how far apart they may come to be. When a photon

produces two daughter photons by spontaneous parametric fluorescence or by down-conversion through a non-linear crystal, their respective energies must sum to that of the parent photon. Their connection manifests itself, for example, by their correlated polarizations. When the polarization of one daughter photon is measured, its entangled partner instantly exhibits a correlated value, no matter how far apart they may be in the Universe (20).

Entanglement can now be understood as a “B” operation occurring in M4. Because of the non-local field  $\{Z\}$ , when the parent (or “pump”) photon is down-converted, it does not “experience” the separation. As we have seen,  $\{Z\}$  compels the properties of the daughter photons (also called “signal” and “idler”) to always sum up to that of the original one. Entanglement has been considered to contradict SR. This is because the non-simultaneity of events seen as simultaneous when viewed in a different inertial reference frame contradicts the simultaneity effect required by entanglement (21) (see next paragraph).

#### ENTANGLEMENT IN REFERENCE FRAMES IN RELATIVE AND ACCELERATED MOTIONS:

In a blockworld universe, four-dimensional spacetime can be foliated by space-like hypersurfaces in an indenumerably infinite number of ways. A hypersurface represents the simultaneity of events for a given observer and observers in relative motion are associated with different hypersurfaces. In figure 8, observer A belongs to the inertial frame  $\{S\}$ . We can imagine two entangled photons, with states **a** and **b**, which are always anti-correlated (i.e. negatively correlated) when measured in  $\{S\}$ . Because of the blockworld principle, those correlations are frozen with regard to spacetime (we consider the photons’ trajectories to be one-dimensional and to represent multiple trials). Observers B and C are on different hypersurfaces than A. It can be readily seen that those observers (and therefore their respective hypersurfaces) are expected to always experience an entanglement of the photons’ states, although this entanglement might be positively or negatively correlated depending on the relative speed: Observer B sees the positively correlated states **b** and **b**, while observer C sees the negatively correlated states **a** and **b**, just like observer A.

An accelerating observer is actually moving from one hypersurface to another, with the associated correlations changing with each hypersurface. This accelerating observer would therefore be expected to experience a deterioration of the entanglement of the two photons, while a non-accelerating observer would still experience the entanglement. In the case of infinite acceleration, the observer is instantly brought to a certain final relative speed correlating with a specific hypersurface where the correlations are constant (bypassing intermediate speeds where correlations alternate). There would therefore be a tendency for entanglement to reappear with infinite acceleration. Those are the results expected when this problem is approached from a quantum information theoretic point of view (22, 23).

#### THE QUANTUM ERASER EXPERIMENT:

The quantum eraser experiment set up is, in principle, similar to the two slits experiment of Thomas Young. According to the current QM interpretation, it is the lack of

knowledge of the which-path information that leads to an interference pattern at the screen. If the path taken by each photon is known (for example by placing detectors D along paths A and B), the interference pattern disappears and only the diffraction pattern of each slit is observed (Fig. 9).

In this experiment, the path of the photon is determined by placing circular polarizers (called labelers, L) of opposite senses in front of each slit. This labels the incoming photons as having traveled through slit 1 or slit 2 when their opposite helicities are measured at the screen (Fig. 10). According to QM, this which-path knowledge destroys the interference pattern. The second step of the experiment is to place a linear polarizer E just before the screen which erases the handedness of the photons and therefore the which-path information (Fig. 11). With that information erased, the interference pattern reappears. A variant of this experiment uses orthogonal polarizations through half-wave plates. It follows the same principles and gives the same results (24, 25).

From the point of view of this paper, the quantum eraser experiment is recognized as an “A” operation. The “information” wave behaves as a classical wave: The parent wave divides at the slits and gives two resulting waves. The opposite helicities created by manipulating the geometry of the waves with the polarizers would make any interference impossible and therefore destroy the interference pattern. The linear polarizer removes the opposite helicities of the resulting waves traveling through slit 1 or slit 2 and allows them to interfere again. The photon manifests only where the wave exists.

#### THE DELAYED CHOICE QUANTUM ERASER EXPERIMENT:

This experiment uses a more complicated set up with the use of parametric down-converters placed in a Mach-Zehnder-type interferometer (Fig. 12). According to QM, a first beam splitter gives a 50% chance that a photon will travel one way or the other. A set of mirrors routes the photons toward a screen where an interference pattern is seen if there is no which-path information. The which-path information can be obtained by placing a down-converter (DC) on each side of the interferometer. This produces two daughter photons called respectively “signal” and “idler” photons (on each side of the apparatus): The signal photon proceeds to the measuring screen, while the idler photon is routed toward separate detectors (D1 and D4). Detection of the idler photon gives which-path information and therefore destroys the interference pattern.

The eraser part of the experiment is done by routing the idler photons originating from each separate path toward a second beam splitter and a third set of detectors (D2 and D3). This set up insures that the which-path information is lost for those signal photons whose idler partners record at those detectors. Therefore, if idler photons are recorded at detectors D2 and D3, the associated signal photons recreate an interference pattern at the interferometer’s screen. The “delayed choice” comes from the fact that each idler photon hits the second set of detectors after its associated signal photon hits the primary screen. The fact that the idler photon hits the first (D1, D4) or second (D2, D3) set of detectors in the future correlates with the fact of an interference pattern being observed or not in the present. Something that occurs in the future therefore appears to influence something that happens in the present. In the current state of the experiments, the idler photon is detected

only a few nanoseconds (about 8ns) after the signal photon, but in theory, there is no time limit as to when the idler photon might be detected and this can theoretically happen even months or years later (26, 27). This allows the extraordinary trans-temporal effects noted in the delayed quantum eraser experiment. Some see a “backward causation” in those effects (28).

From the point of view of this paper, the delayed quantum eraser experiment is recognized as a combination of “A” and “B” operations: The wave associated with the parent photon divides at the first beam splitter (“A” operation) and each resulting wave divides again at the down-converters (“B” operation) into daughter “signal” waves going toward the screen and daughter “idler” waves going toward the second set of detectors. In the absence of the down converters, the parent waves would create an interference pattern. The down converters create *entangled daughter waves* on each side of the apparatus (there is no entanglement from one side of the apparatus to the other). Those are different from the original parent wave and the waves of each side of the apparatus are separated from each other and do not interact (Fig. 13). The associated signal photons will therefore not give rise to an interference pattern if their respective idler photons manifests at the D1 or D4 detectors.

In the eraser part of the experiment, both daughter “idler” waves are directed toward the second beam splitter (another “A” operation) which in fact *recombines* the idler waves from each side of the apparatus at the third set of detectors (D2 and D3) (Fig. 14). When a photon manifests at one of those detectors, it is therefore associated with recombined “idler” waves, this time from both sides of the apparatus which compel their respective associated signal waves to create an interference pattern at the screen (one recognizes here an “A” operation). From a geometrical standpoint, the waves behave classically.

“A” operations therefore determine whether there will be an interference pattern or not. “B” operations determine whether there will be a trans-temporal effect or not. Lengthening the path of the idler photons (or waves) on each side of the apparatus is equivalent to the “tilting” of the wave system of figure 5, which creates correlations across time (again, entangled signal and idler waves are created on each side of the apparatus by the down-converters; there is no entanglement from one side of the apparatus to the other).

Figure 15 shows what happens to the two down-converted photons on one side of the apparatus on a Minkowski diagram (also compare to figure 5). We can consider the trajectories one-dimensional due to the optical apparatus used. **A** is the down-conversion event. **AB** represents the path of the signal photon, while **ACD** represents the path of the corresponding idler photon. **B** and **C** would be simultaneous events as seen in the **t** inertial reference frame where the two photons originate. The signal photon is measured at **B**, while the idler photon is actually measured at **D**, which lies in the future of **B** in the inertial reference frame **t**. At **B** and **D**, the two photons are non-locally connected through **{Z}** (as they are on the null cone) and, therefore, would always give correlated results to measurements. As the figure shows, there always exists an inertial reference frame (of time axis **t'**) where the two events **B** and **D** are simultaneous. Geometrically, the picture

trivially shows that the  $\mathbf{t}'$  inertial reference frame is tilted with respect to  $\mathbf{t}$  and that the angle between  $\mathbf{t}$  and  $\mathbf{t}'$  is always less than  $45^\circ$ , no matter how far apart  $\mathbf{B}$  and  $\mathbf{D}$  might be in spacetime. The diagram is simplified for the sake of visualization. To have a full picture of the experiment, we would actually need twin diagrams, next to one another, to show the two signal photons (one from each side of the apparatus) interacting (or not) at  $\mathbf{B}$ , and the two idler photons (again, one from each side of the apparatus) being routed toward the  $\{D2, D3\}$  or the  $\{D1, D4\}$  sets of detectors at  $\mathbf{D}$  (the delayed choice). However, this would unnecessarily burden the diagram. As there will always be an observer that sees the two events as simultaneous, the author prefers to consider them “correlated across time” rather than invoke “backward causation”.

#### THE COMPTON EFFECT:

In 1916, Einstein proposed that light quanta have linear momentum and that both energy and momentum are transferred when a photon interacts with matter “as if there was a collision ... in the classical sense” (29). In 1923, Arthur Compton directed a beam of x-rays at a carbon target. This produced a scattering of the x-rays with a range of wavelengths, each related to the scattering angle (the larger the angle, the longer the wavelength and therefore the less the energy). Compton interpreted the results in terms of “collisions” (with transfer of energy and momentum) between the x rays’ photons and loosely bound electrons in the target. This also demonstrated that the “elementary” energy of photons is not that “elementary” after all and can be divided under certain circumstances.

According to Penrose, the Dirac equation for the electron can be rewritten in terms of a “2-spinor notation” (30). The equation couples the two 2-spinors with a mass related “coupling constant” where each 2-spinor acts as a source for the other. This gives a picture of two massless particles (named “zig” and “zag”) continuously converting into one another and “jiggling” back and forth at light speed. Penrose states: “this is a realization of the physical event referred to as “zitterbewegung” according to which, the electron’s instantaneous speed is always measured to be the speed of light, owing to the electron’s jiggling motion, even though the overall averaged motion of the electron is less than light speed”. Penrose admits that this approach is non-standard, but what is of interest in this model is that the electron has components that move at light speed (the zig and the zag). As such, it has a valid existence in  $\{Z\}$ .

The interaction between an EMW and an electron can therefore be regarded as a general “B” operation between two light speed waves: Their energy and momentum are therefore subject to arithmetic operations in  $\{Z\}$  (they sum, subtract, multiply and divide accordingly). Their sums must also remain constant functions. All that is necessary at this point is to recognize that this is equivalent to the energy and momentum conservation laws which are the basis of the Compton shift formula. Everything happens *as if* the EMW-electron interaction was an elastic collision. EMW scattered at wider angles will exhibit less energy, just as observed by Compton.

As was previously noted, one implication is that the zero-dimensional space  $\{Z\}$  may play an important role in the genesis of energy's conservation laws, at least as far as particles are concerned.

Another implication is that any particle exhibiting quantum properties *must have a component moving at light speed*, in a sense similar to Penrose's non-standard approach to the nature of the electron.

#### THE PILOT-WAVE OF DE BROGLIE AND BOHM:

According to Holland, "The fundamental physical assumption of the de Broglie-Bohm theory is the objective (co)existence of the quantum wave and the particle it guides". According to this theory, the quantum wave has a real existence (i.e. it is not a probability wave in Hilbert space) and guides (pilots) a particle which also has a real existence. The wave possesses classical wave properties and can exist in superposed states. Because the particle's reality remains one despite the wave's multiple superposition states, the measurement problem is readily solved. The theory also defines a "quantum potential" that permeates spacetime and accounts for the non-local correlations seen with entanglement (31).

In the conceptual framework of this paper, the LSW also has a real existence with classical properties. However, as has been seen, it is felt that a light speed "particle" can only exist as information carried by the wave. This information transforms into "realness" only when a decoding process occurs (for example, a measurement). Therefore, the "particle" is not "real" in the sense of the de Broglie-Bohm approach and does not have an independent existence of its (pilot) wave. Both approaches, however, lead to the avoidance of superposed realities.

The de Broglie-Bohm "quantum potential" has similar properties to the zero-dimensional space  $\{Z\}$  considered in this paper. It permeates all spacetime and has non-local effects. However, the concept of "quantum potential" is derived from a reformulation of the Schrödinger equation within the mathematics of QM, while the concept of the zero-dimensional space  $\{Z\}$  is derived from geometrical considerations of the proper frame of the photon within SR.

#### THE QUANTUM INFORMATION THEORY OF BUB:

Quantum Information Theory (QIT), as discussed by Bub, leads to three fundamental information-theoretic constraints (known as the Clifton, Bub, and Halvorson Characterization Theorem): 1/ "the impossibility of superluminal information transfer", 2/ "the impossibility of perfectly broadcasting the information contained in an unknown physical state" (which becomes the no cloning theorem for pure states), and 3/ "the impossibility of communicating information so as to implement a bit commitment protocol with unconditional security". This, by reciprocal arguments, characterizes QM theory as those constraints entail that "the algebras of observables of distinct physical systems commute ...", that "any individual system's algebra of observables is *noncommutative*" and that "the physical world is *non-local*" (32). For Bub, QM becomes "a theory about the representation and manipulation of information constrained by the

possibilities and impossibilities of information-transfer in our world, rather than a theory about the ways in which nonclassical waves and particles move”.

QIT does not address the question of the physical nature of the quantum of light (or of gravity). In this it differs from the current framework which defines the physical reality of this quantum as (classical) *information* which manifests as a “particle” when an interaction or measurement occurs. The concept of *information* is therefore used very differently in QIT and in the current approach. In QIT, it is used in a more general way as an information-theoretic treatment of the mathematical formalism of QM, while in the current approach it is applied to the physical nature of the quantum of light or gravity themselves. In other words, in QIT, information is part of a theory about reality, while in the present conceptual framework it is a *component* of reality.

#### SPECIAL RELATIVITY AND QUANTUM MECHANICS:

Is there a relation between SR and QM? We have seen that SR can support a non-local field and a probabilistic component to the manifestation of a photon. With this we have been able to shed some light on some quantum physical events not clearly explained by QM and this seems to imply some common ground between the two theories. However, there is more to the construction of QM than can be derived from the above considerations, such as the concepts of superposition and decoherence, the development of the Schrödinger or Heisenberg representations, the determination of expectations values and the dynamic evolution of the wavefunction. QM is not considered to reside in  $M_4$  where  $\{Z\}$  exists and it is therefore unclear whether the zero-dimensional non-local field  $\{Z\}$  can be related to the non-local field of QM. Nevertheless, Dirac used  $M_4$  to develop his relativistic QM theory of the electron but this doesn't seem to have been expanded to the determination of the nature of the non-local field (33). There appears to be two reasons why this was not done: most QM problems do not involve relativistic speeds and there has been a widespread belief that  $M_4$  could not support a non-local field as expressed by Dirac himself (as previously noted (34)). Whether a relation might exist between SR and relativistic QM will have to be the subject of further inquiry.

#### CONCLUSION:

This paper has shown that SR predicts a non-local field which is zero-dimensional in nature. This zero-dimensional field, that we have named  $\{Z\}$ , compels the energy of a light speed wave to manifest at only one location and be quantized. This fact and the associated non-locality seem to readily explain previously mysterious quantum physical events such as quantization, entanglement and the measurement problem. By extension, those concepts have allowed us to shed some light on some experiments such as the delayed quantum eraser and the Compton scattering. To simplify the discussion, we have systematized some quantum physical events into “A” and “B” operations. While those may appear to simply be a restatement of the wave/particle duality, “B” operations are wave-like and embed zero-dimensional non-locality. They cannot be considered equivalent to what is generally understood by a “particle”. Under this approach, Compton scattering and entanglement appear to be variations of the same general process and the zero-dimensional field  $\{Z\}$  seems to play a role in the conservation laws of energy. Under this view, all quantized particles might have a light speed component.

We have also shown a different way to look at the trans-temporality of entanglement in the delayed choice quantum eraser experiment and questioned the concept of backward causation. This approach obliged us to posit that what is actually carried by a light speed wave is not the energy itself but information (taken in the classical sense) that manifests as energy when a measurement is made or when an interaction occurs. According to this view, information is not an abstract concept about reality but an integral part of this reality. These concepts have shown some common ground between Special Relativity and Quantum Mechanics although a relation cannot be claimed.

Einstein seems to have underestimated Special Relativity. He would have been very surprised by the fact that Special Relativity can predict a non-local field. But, after all, there is a “flavor” of non-locality in the postulates of Special Relativity. The statement “the speed of light in the vacuum is constant in all inertial reference frames” can be rephrased as “there is an instantaneous correlation between the speed of light at a given point  $x$  and the speed of light at another point  $y$ , no matter how far apart those points may be and in which inertial reference frame each may exist”. It is hoped that the above considerations will inspire new directions of inquiry for the search of a theory that would encompass both SR and QM.

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# THE SIGNIFICANCE OF THE PROPER FRAME OF THE PHOTON FOR THE EPISTEMOLOGY OF QUANTUM MECHANICS

## CAPTIONS

FIGURE 1: The two slits experiment of Thomas Young. Light emitted by the source  $S$  follows paths  $A$  and  $B$ . An interference pattern at the screen demonstrates the wave nature of light.

FIGURE 2: A snapshot measurement of an electromagnetic wave (EMW) performed at point  $A$  shows no distance or time interval, but a speed  $c$  ( $t$ : time axis;  $s$ : space axis;  $\{S\}$ : inertial reference frame).

FIGURE 3: According to the blockworld concept, all points  $x$  of the EMW coexist, each with its own energy  $E$ . As all points collapse in  $\{Z\}$  where their energies sum up, this would give the wave infinite energy in  $\{Z\}$  ( $\{Z\}$ : zero-dimensional space defined by the proper frame of the photon).

FIGURE 4: A light speed wave (LSW) (for example an EMW) is down-converted (DC) into two daughter waves.  $\{Z\}$  sees no separation and the properties of the daughter waves (energy, momentum, spin, etc ...) must always sum up to the values of those same properties in the parent wave, i.e. the daughter waves are entangled and will give correlated results when measured simultaneously (dotted line).

FIGURE 5:  $\{Z\}$  is indifferent to the geometry that a LSW may adopt in spacetime. The wave system of figure 4 (now designed  $[\mathbf{o}, \mathbf{a}, \mathbf{b}]$ ) may be rotated to give the system  $[\mathbf{o}', \mathbf{a}', \mathbf{b}']$ . While  $\mathbf{a}$  and  $\mathbf{b}$  show an entangled correlation in the present of the inertial reference frame  $\{S\}$  (dotted line),  $\mathbf{a}'$  and  $\mathbf{b}'$  show an entangled correlation respectively in the future and the past of that present. This is what is thought to happen in the delayed choice quantum eraser experiment (**DC**: down-conversion).

FIGURE 6: Schematic of a general “B” operation.  $\mathbf{a}$  and  $\mathbf{b}$ : input waves;  $\mathbf{c}$  and  $\mathbf{d}$ : resulting or output waves;  $\mathbf{I}$ : interaction;  $\{S\}$ : inertial reference frame where the system exists;  $\{Z\}$ : zero-dimensional space. All waves exist in  $\{Z\}$  and therefore, their properties must at each instant sum up to constants.

FIGURE 7: Circular propagation of an electromagnetic wavefront.  $\mathbf{O}$ : point source.  $\mathbf{A}$ : manifestation of the photon.  $\mathbf{x}$  and  $\mathbf{y}$ : Cartesian coordinates of the system.

FIGURE 8:  $\mathbf{B}$  and  $\mathbf{C}$ : observers in relative motion with respect to an inertial reference frame  $\{S\}$ .  $\mathbf{A}$ : observer belonging to  $\{S\}$  whose line of simultaneity determines the present of  $\{S\}$ .  $\mathbf{a}$  and  $\mathbf{b}$ : anti-correlated states of two entangled photons, frozen in time according to the blockworld concept.

FIGURE 9: Detectors (D) are placed at the slits of the figure 1 experiment, giving which-path information about the photon. With the knowledge of the which-path information, the interference pattern is lost and only a diffraction pattern emerges.

FIGURE 10: The Quantum Eraser Experiment (part 1): Labelers (L) are placed in front of the slits giving which-path information. The labelers act as the detectors of figure 8 and the interference pattern is lost.

FIGURE 11: The Quantum Eraser Experiment (part 2): An eraser (E) placed just before the screen removes the which-path information. The interference pattern is reestablished.

FIGURE 12: Mach-Zehnder type interferometer. S: Source. DC: Down Converters. D1, 2, 3, 4: Photons Detectors. Small white oblique rectangles: Beam-splitters. Small black oblique rectangles: Full mirrors. Here the result at the screen is completely random.

FIGURE 13: The Delayed Choice Quantum Eraser Experiment (part 1): Thick lines: Entangled daughter waves associated with signal and idler photons. The daughter waves created by each down-converter (DC) remain separated from each other and there is no interference pattern (each being on a different side of the apparatus; there is no entanglement from one side to the other).

FIGURE 14: The Delayed Choice Quantum Eraser Experiment (part 2): Thick lines: Entangled daughter waves associated with signal and idler photons. This time the idler daughter waves created by each down-converter recombine at D2 and D3, compelling their respective signal waves to interfere at the screen (again there is no entanglement from one side of the apparatus to the other).

FIGURE 15: Minkowskian representation of the signal and idler photons from one side of the apparatus used for the delayed choice quantum eraser experiment (compare to figure 5).

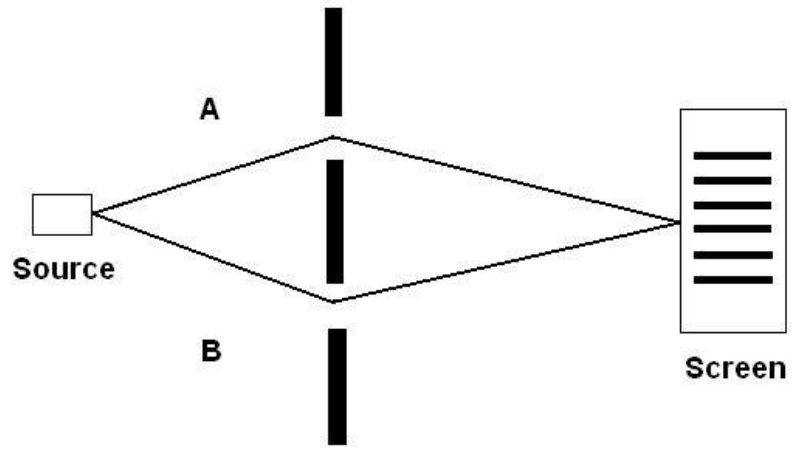


Figure 1

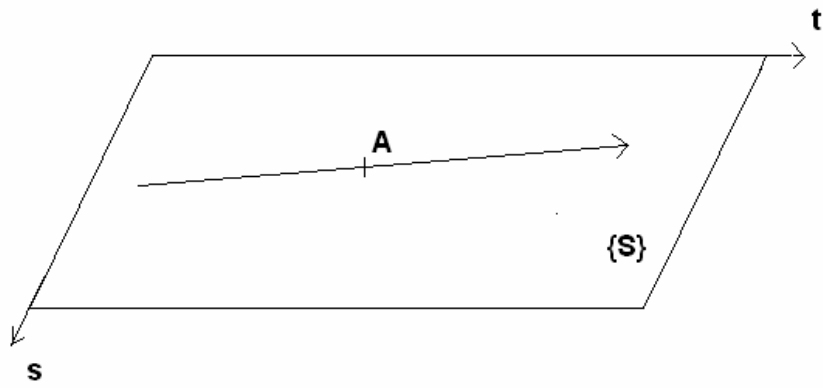


Figure 2

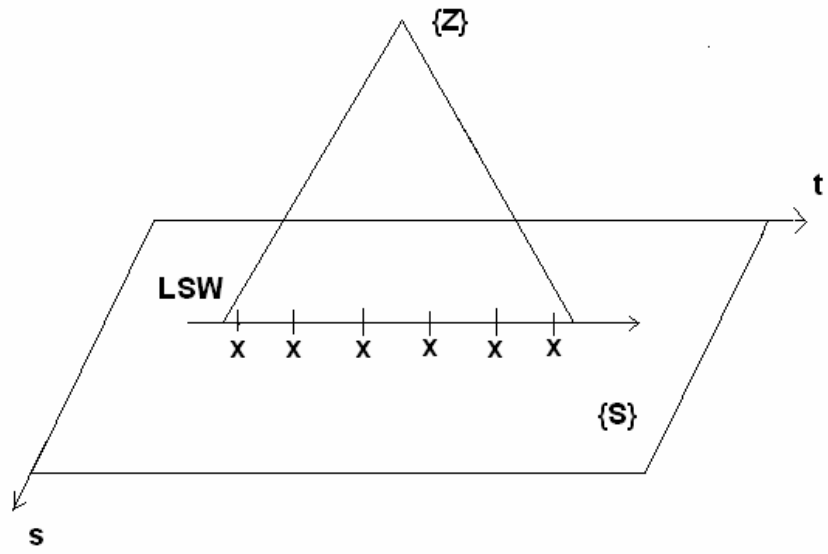


Figure 3

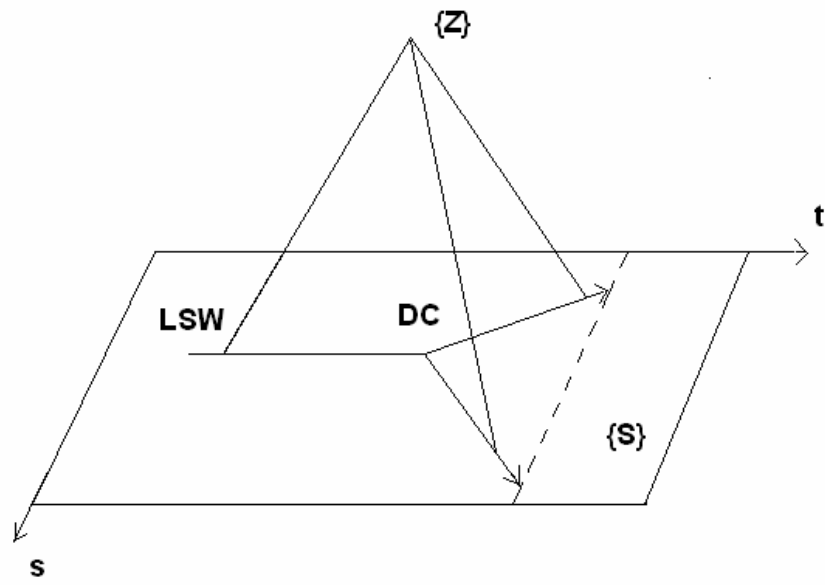


Figure 4

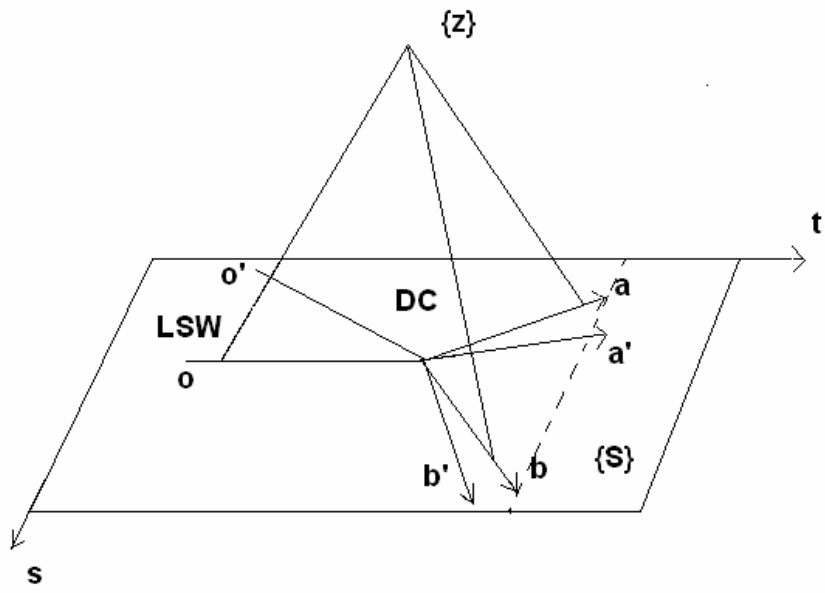


Figure 5

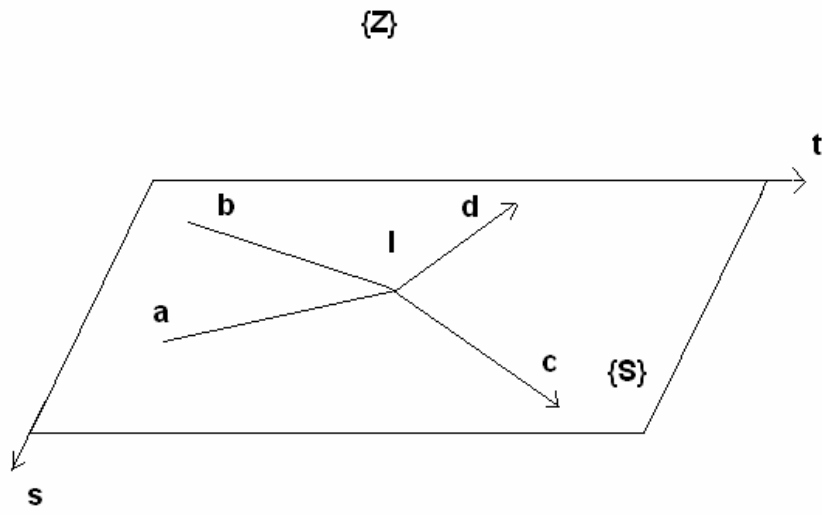


Figure 6

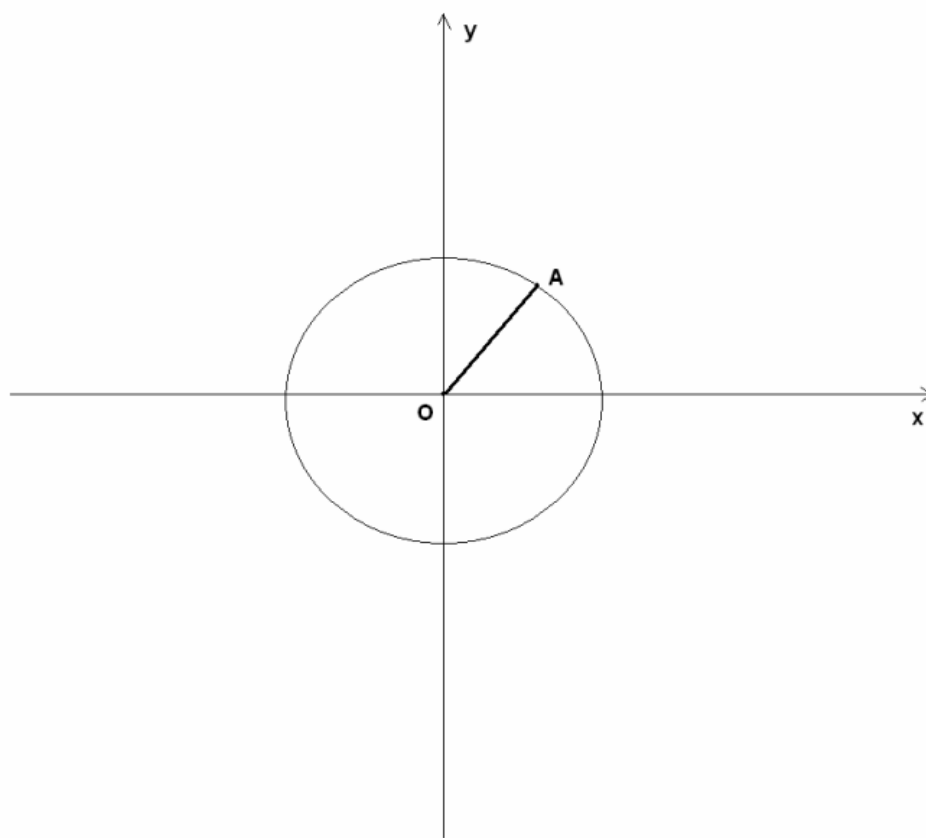


Figure 7

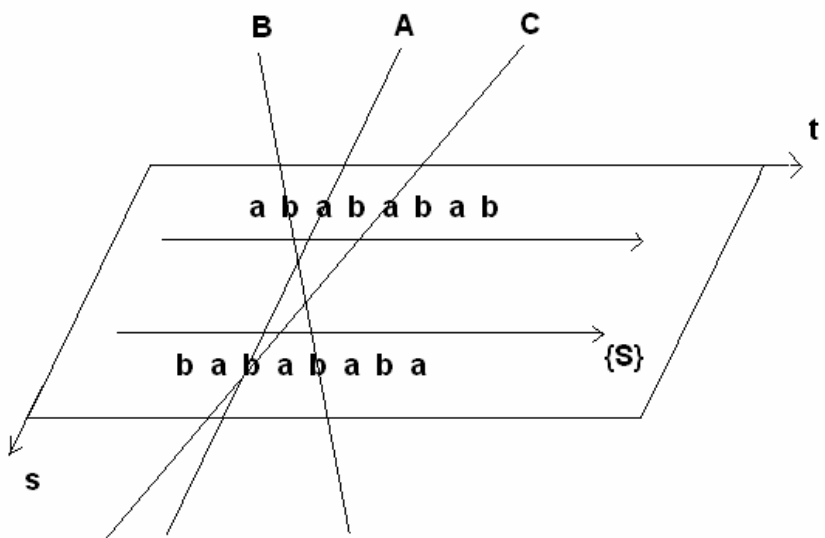


Figure 8

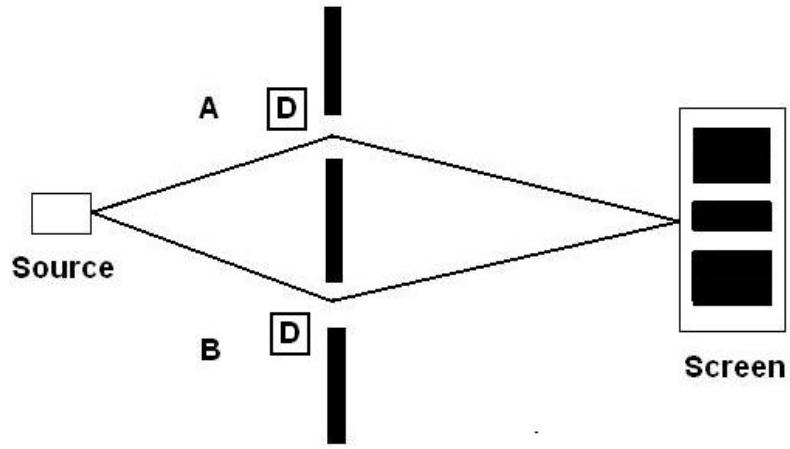


Figure 9

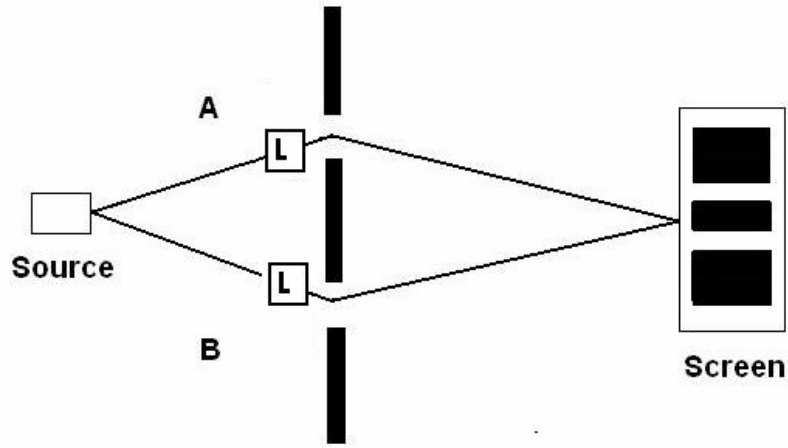


Figure 10

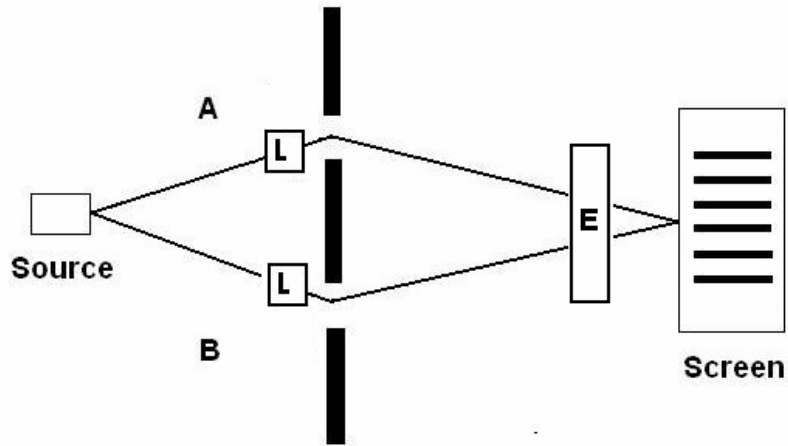


Figure 11

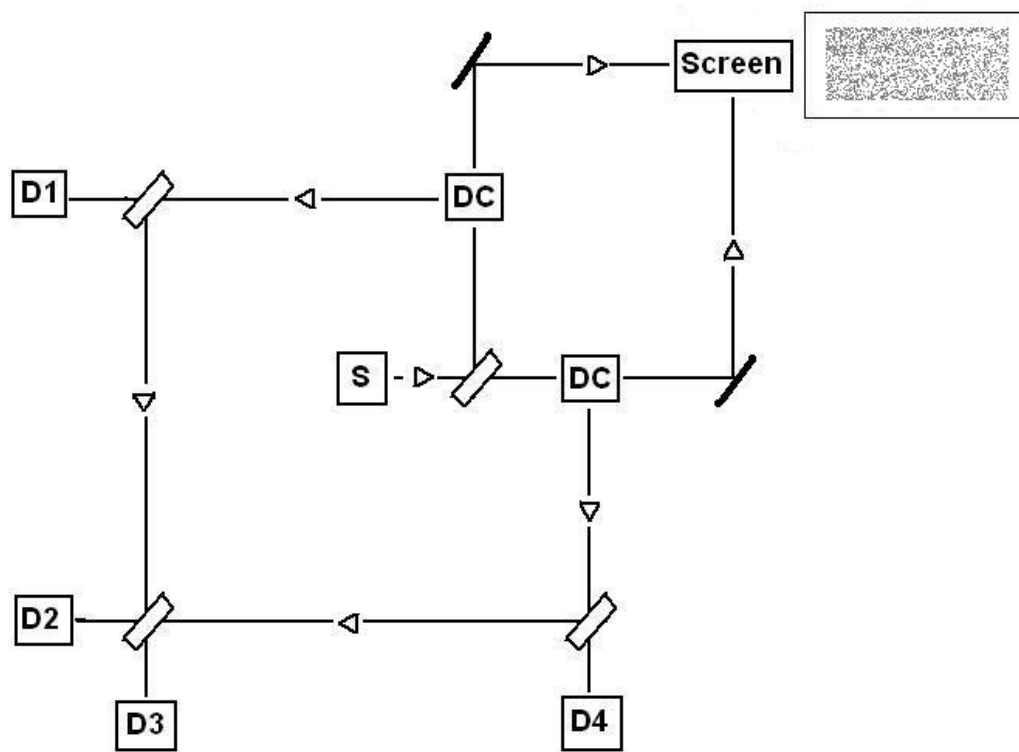


Figure 12

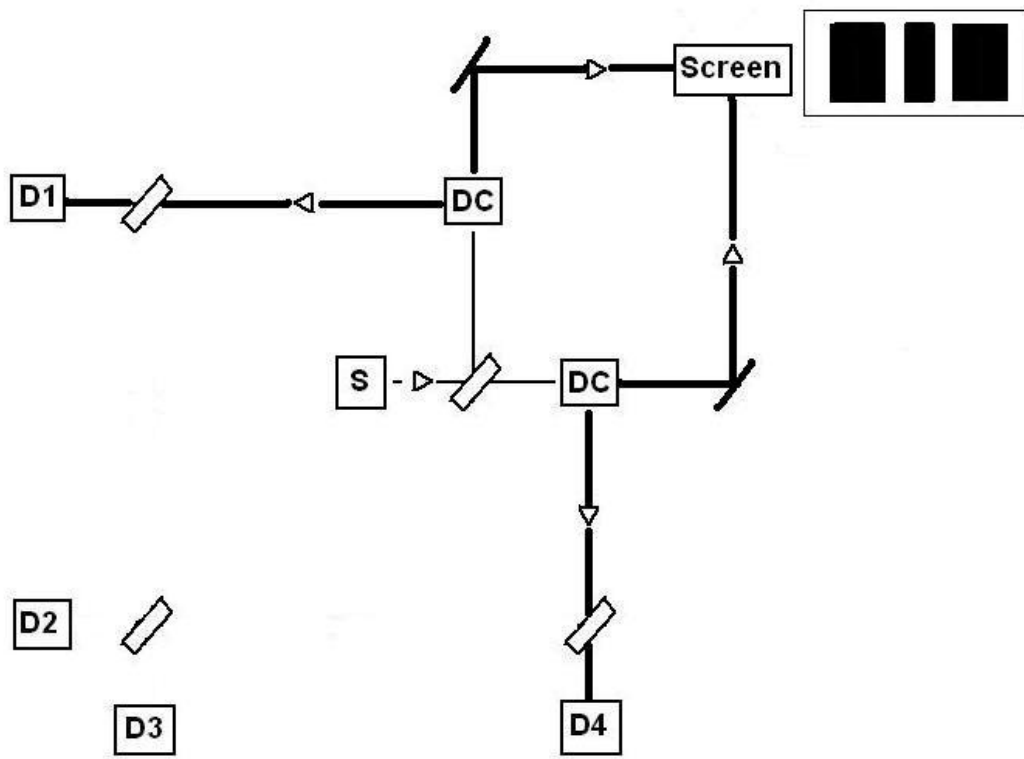


Figure 13

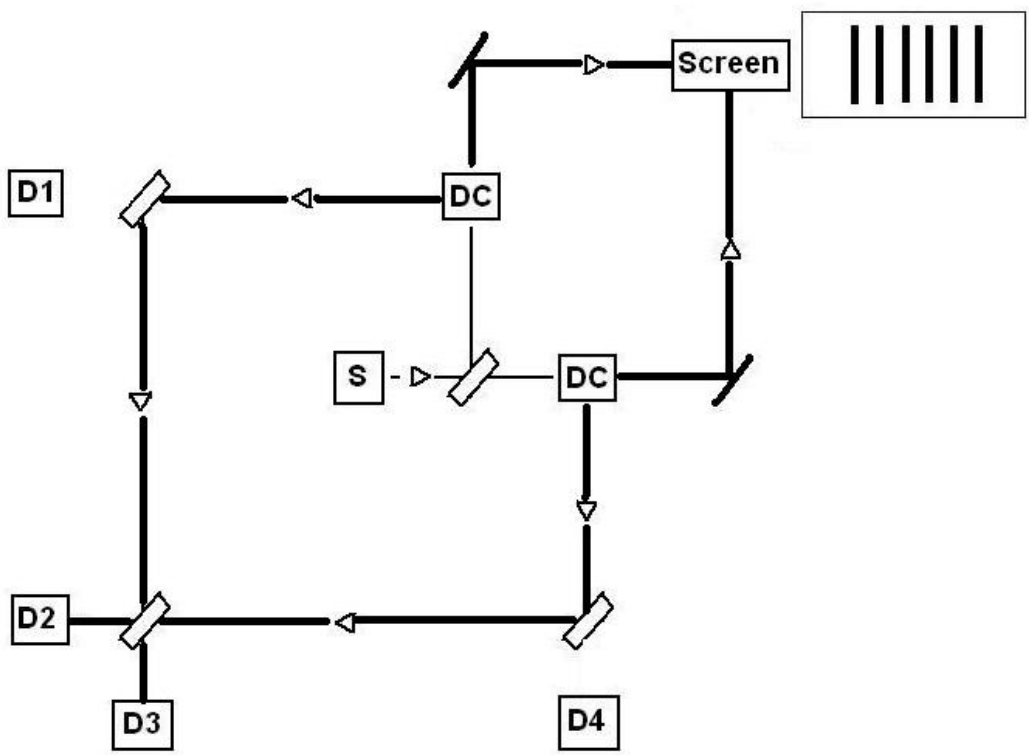


Figure 14

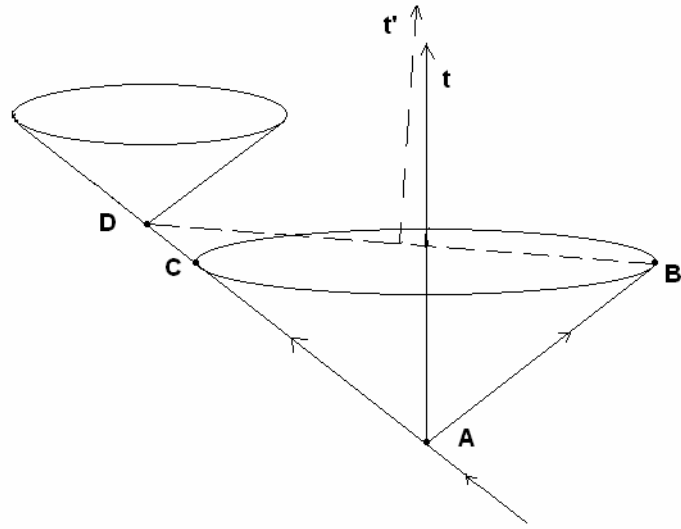


Figure 15