

Paths of Least Time for Quantum Scale and Geometrical Interpretation of Light Diffraction

F. BEN ADDA*

September 9, 2014

Abstract

In this paper, a geometrical interpretation of light diffraction is given using an infinity of fluctuating geodesics for the small scale (the quantum scale) that represent paths of least time in an homogeneous space. Without using the wave theory, we provide a geometrical explanation of the deviation of light's overall direction from rectilinear when light encounters edges, apertures and screens.

Pacs: 02.70.-c, 42.25.Hz

1 Introduction

The quest for the comprehension of the real nature and properties of light has involved, for centuries, a big number of scientists and researchers such as Ibn Alhaitham, Descartes, Newton, Grimaldi, Young, Huygens, Fresnel, Maxwell, Hertz, Röntgen, Von Laue, Planck, Einstein, Bohr, Compton, De Broglie, Davisson, Paget Thomson, Schrödinger, Dirac, Tomonaga, Schwinger, Feynman, Dyson and others ([1], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [34], [35]). The progress of research in the 19th century has shaped our way of thinking about the nature of light. The significant progress of the quantum theory based on experimental results and observations for the small scale world dictate our understanding of the nature of light and influence the way one can approach the photon's motion and nature.

The indeterminacy based on the Heisenberg's uncertainty principle imposes the non consideration of paths and trajectories for elementary particles and photons. This difficulty is optimized by the use of density of probabilities of particle position, where the state of an elementary particle is entirely given by the wave function (a unit vector in Hilbert space) that verifies Schrödinger equation, meanwhile the wave associated to the photons verifies the electromagnetic wave equation.

Providing a geometrical explanation of the light diffraction passes thought trajectories and the principle of least time. In order to be in conformity with the indeterminacy of the fundamental principle of quantum mechanics (Heisenberg's uncertainty), we will use in this work an infinity of paths of least time for the photon's motion that minimize the total time needed for the photon to travel between two locations without determination of a particular

*New York Institute of Technology. Email: f.benaddafr@yahoo.fr

path. We will use an infinity of possible paths (that have the same length) for the photon to travel between the two distant locations.

If a quantum physical system in a given space-time is in free motion from one location to another following the path that requires the shortest time, then the geometry of the space-time could dictate the behavior of the physical system in following the curve that minimizes the total time needed to travel between the two locations (this concept is used in cosmology with the so-called cosmological redshift: the light wavelength increases as it propagates through an expanding space by the same amount ([17]), which means that the expansion of the space affects the wavelength). If there exists some "interaction" between the expanding space and light that makes its wavelength increases by the same amount as it propagates through the expanding space, then the light motion must be shaped by the space characteristics (such as geodesics and paths of least time).

Interesting geodesics are found in the simulation of an expanding space-time [3], that expands via expansion of its basic elements, where the path of least time is found to be given by an infinity of fluctuating geodesics directed by a geodesics axis that indicates the overall displacement, and minimizes the total time needed to travel between two distant locations in an homogeneous space. The use of these geodesics has led to reproduce an interference pattern similar to the interference pattern observed in Young's double-slit experiment under the assumption that all possible geodesics of the physical system, that represent paths of least time and that passe through an opening, flare out (diffract) and cover an angle beyond the slit (see [4]). The deviation of the physical system's geodesics direction from rectilinear, when it passes through a narrow slit and creates the diffraction, is explained within this paper, which will complete the geometrical explanation of interference pattern of Young's double-slit experiment introduced in ([4]) without using the wave theory.

2 Prototype of Space-Time Fluctuating Geodesics

2.1 Fluctuating Geodesics in the Plane

Let us consider a physical system in a free motion between two distant locations A and B, in a given homogeneous space-time, following the path that requires the shortest time, and let us assume that the space-time geodesics are defined (see [3] for more details) by φ given by

$$\varphi(x) = \sum_{i=0}^{N-1} g_i(x), \quad \text{for } N \geq 1 \quad (1)$$

where

$$g_i(x) = \begin{cases} \varphi_i(x) & \text{for } x \in [2ir, 2(i+1)r] \\ 0 & \text{for } x \notin [2ir, 2(i+1)r] \end{cases} \quad (2)$$

and

$$\begin{aligned} \varphi_i : [2ir, 2(i+1)r] &\longrightarrow \mathbb{R} \\ x &\longmapsto \varphi_i(x) = (-1)^i \sqrt{r^2 - (x - (2i+1)r)^2}, \end{aligned} \quad (3)$$

that verifies:

i) for $i = 0, \dots, N - 1$, the graph of φ_i represents the geodesic between two antipodal points on the circle of center $C_i = ((2i + 1)r, 0)$ and radius r ;

ii) for $i = 0, \dots, N - 1$, φ_i is continuous on the closed interval $]2ir, 2(i + 1)r[$;

iii) for $i = 0, \dots, N - 1$, φ_i is differentiable on the open interval $]2ir, 2(i + 1)r[$;

iv) for $i = 0, \dots, N - 1$, φ_i is not differentiable at the points $x_i = 2ir$ and $x_{i+1} = 2(i+1)r$.

The graph of these geodesics is illustrated for a given r in Fig.1.

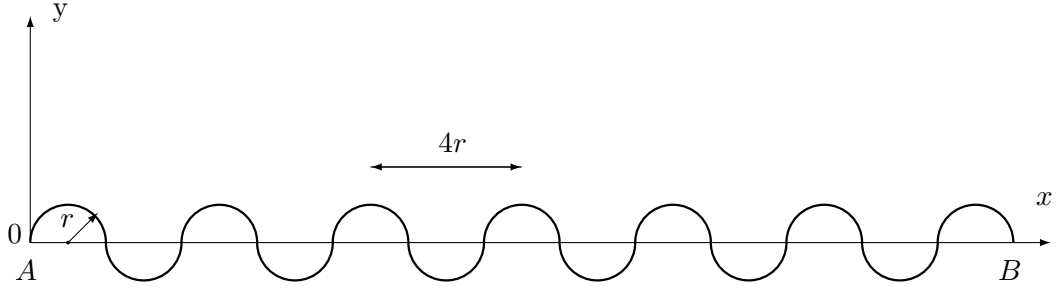


Figure 1: Geodesic in 2D for $N = 13$ and radius $r = 5 \text{ mm}$ between two points A and B on the x -axis.

Based on property i), it is impossible to determine which geodesic represents the path that requires the shortest time between the two distant locations $A = (0, 0)$ and $B = (x, \varphi_i(x))$ for $i = 0, \dots, N - 1$. Indeed, there exist two opposite geodesics between two antipodal points on the circle of center $C_i = ((2i + 1)r, 0)$ and radius r for all $i = 0, \dots, N - 1$, then between $A = (0, 0)$ and $B = (x, \varphi_i(x))$ for $x \in]2ir, 2(i + 1)r[$ there exist

$$\begin{cases} 2^N \text{ geodesics,} & \text{if } x = 2(i + 1)r; \\ 2^{N-1} \text{ geodesics,} & \text{if } x \in]2ir, 2(i + 1)r[. \end{cases} \quad (4)$$

that represent paths of least time between the two locations A and B . Any physical system that follows the path of least time given by (4) in the plane will have 2^N or 2^{N-1} possibilities, then it is impossible to predict from which path the physical system will pass through because all of them represent paths of least time in two dimensions.

2.2 Fluctuating Geodesics in the Space

To obtain all possible geodesics between two distant locations in three dimensions using the geodesic (1), we use a rotation of the graph of the function (1) about the x -axis (see Fig.2). Indeed, if we denote the graph of φ by

$$G_\varphi = \{(x, y, z) \in \mathbb{R}^3 / y = \varphi(x), z = 0\} \quad (5)$$

then the graph of all geodesics in three dimensions is given by

$$G_{R_\theta(\varphi)} = \left\{ (x', y', z') \in \mathbb{R}^3 / \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = R_\theta \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \text{ with } \begin{pmatrix} x \\ y \\ z \end{pmatrix} \in G_\varphi \right\} \quad (6)$$

where R_θ is the rotation about the x -axis of angle $\theta \in [0, 2\pi]$ given by

$$R_\theta = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{pmatrix} \quad (7)$$

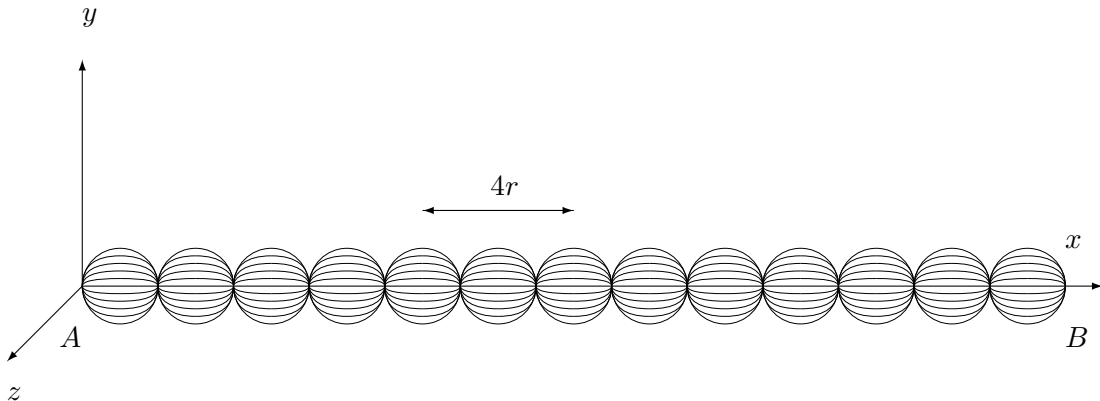


Figure 2: Geodesics in 3D for $N = 13$ and radius $r = 5 \text{ mm}$ between two points A and B.

These geodesics in three dimensions will be considered as light geodesics for the small scale world to provide a rigorous interpretation of light diffraction and to explain why the light flares out (diffracts) into the region beyond the screen of narrow slit.

It is known that one cannot predict which path is followed by photons to travel between two distant locations. If a photon is assumed to follow the geodesics (6) in an homogeneous space-time as paths of least time, then the photon will have an infinity of geodesics between any distant locations $A = (0, 0, 0)$ and $B = R_\theta(x, \varphi_i(x), 0)$ for $i \geq 1$, and $\theta \in [0, 2\pi]$ (since there exists an infinity of geodesics between two antipodal points on the sphere of center $C_i = ((2i + 1)r, 0, 0)$ and radius r). Moreover, since the dimension of the light wave length is between 10^{-6} m and 10^{-7} m , then within 1.1 mm there is 2000 times the average of the light wave length, which means that using the fluctuating geodesics defined in (6) with $4r = 5.5 \times 10^{-7} \text{ m}$, we obtain 4000 points of non differentiability within 1.1 mm , and 4000 extrema. Therefore the infinity of geodesics of least time defined by (6) for $r = 1.375 \times 10^{-7} \text{ m}$ appears as a straight line geodesic for the macroscopic observation.

The fluctuation of a physical system in following one of the infinity of geodesics (6) for the quantum scale is preponderant if the dimension of the physical system is less than $4r$ (two successive extrema), however this motion appears to be a straight line motion if the dimension of the physical system is larger than $4r$.

The existence of an infinity of possible geodesics of least time in an homogeneous space and the existence of a big number of points of non differentiability for each geodesic induce that it is impossible to predict from which path the photon will pass through, and practically it is impossible to measure simultaneously its position and momentum with complete precision, which is consistent with the quantum indeterminacy. However knowing all possible geodesics of least time defined by (6) in an homogeneous space, we will be able to understand what the photon does to travel between the narrow slit and the detector screen without determinacy,

we will be able to provide a geometrical explanation of the deviation of light direction from rectilinear when light encounters edges, apertures and screens.

3 Fluctuating Geodesics and Reflection Laws

Let us assume that when a source emits a single photon in an homogeneous space-time, the photon travels along one path among the infinity of possible geodesics of least time defined by (6) between two distant locations illustrated in Fig.2. The x -axis represents the *geodesics axis* that determines the light overall direction, and the yz -plane represents the plane of geodesics oscillation. The geodesics given by the graph (6) in an homogeneous space-time are resultant of composition of oscillations in the yz -plane and a translation with increasing-decreasing magnitude directed by the *geodesics axis*. The oscillations determine the period, the frequency and the amplitude of the geodesics.

Let us assume in the following that when a photon follows one fluctuating geodesic from the infinity of paths of least time defined by (6) and encounters an interface that induces a specular reflection (mirror for example), the geodesics axis of the photon's path verifies the classical law of reflection, and the angle which the incident *geodesics axis* makes with the normal is equal to the angle which the reflected *geodesics axis* makes with the normal (see Fig.3, (a) and (b)). The local mechanism of reflection of the fluctuating geodesics (6) with different form of interface will be the subject of a further work.

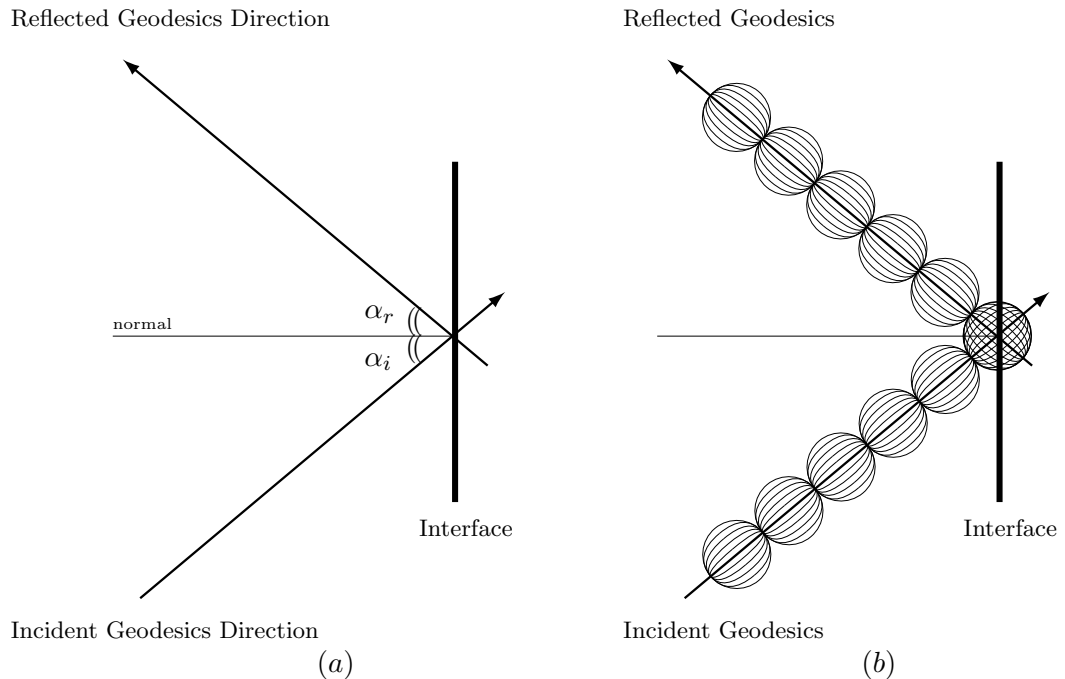


Figure 3: Fluctuating geodesics reflection based on symmetric with respect to the normal line to the interface that passes through the intersection point of incident geodesics axis and reflected geodesics axis. (a) Illustration of reflection of the geodesics axis. (b) illustration of reflection of all geodesics following the geodesics axis.

Nevertheless the illustration of the reflection in two dimensions given in Fig.4 provides an explanation of the local reflection that leads to the global reflection of the geodesics axis: if the photon follows the upper geodesic near the antipodal point A , then the photon follows the arc \widehat{AB} , and is locally reflected at the incident point A following the law of reflection (the tangent line of the photon's incident path and the tangent line of the photon's reflected path at the point of incidence are symmetric with respect to the normal line that passes through the point of incidence). Afterward, the photon follows the arc \widehat{BC} , and is reflected a second time at the incident point C (following the law of reflection), then it follows the arc \widehat{CD} to reach the antipodal point D and to travel following the upper geodesic. If the photon follows the lower geodesic near the antipodal point A , then the photon follows the arc \widehat{AC} , and is locally reflected at the incident point C following the law of reflection. Afterward, the photon follows the arc \widehat{CB} , and is reflected a second time at the incident point B (following the law of reflection), then it follows the arc \widehat{BD} to reach the antipodal point D and to travel following the lower geodesic.

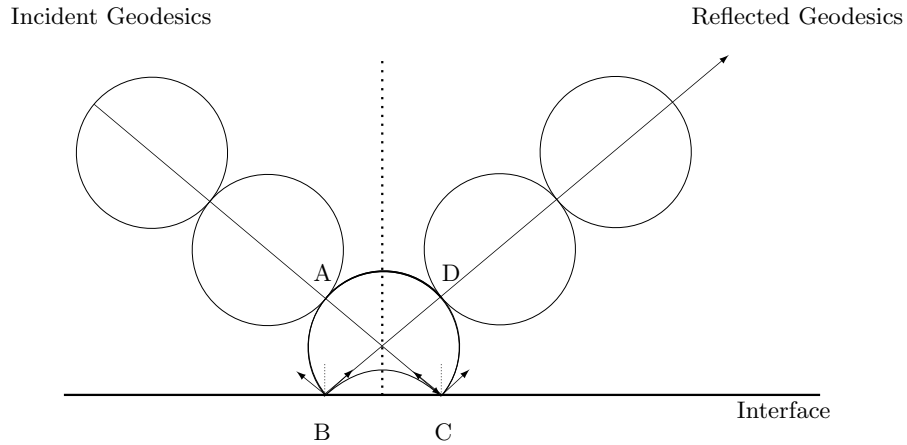


Figure 4: Illustration of reflection of fluctuating geodesics in two dimensions.

4 Fluctuation and Diffraction of Light

Let us consider a photon that travels along one path among the infinity of possible geodesics of least time defined by (6) between two distant locations in a given direction and encounters a barrier that has an opening. The reflection of the photon on the barrier side depends on the path of least time chosen from the infinity of possible geodesic defined by (6) (on the local fluctuation) and the position of the geodesics axis. Three possible cases can occur when the light geodesics encounter the corner of the obstacle of width l (see Fig.5):

i) the geodesics axis is parallel and above the side of width l (the horizontal side of the barrier illustrated in (a), Fig.5);

ii) the geodesics axis is parallel and on the side of width l (the horizontal side of the barrier illustrated in (b), Fig.5);

iii) the geodesics axis is parallel and below the side of width l (the horizontal side of the barrier illustrated in (c), Fig.5).

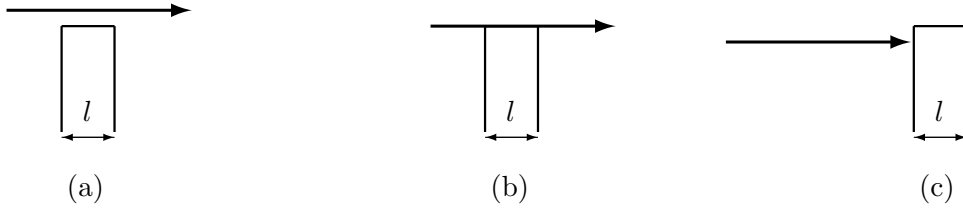


Figure 5: Illustration of the geodesics axis position with respect to the barrier of width l .

For the cases (i) and (ii), using the reflection law locally, the photon passes through the opening and conserves the direction of its geodesics axis, meanwhile for the case (iii), using the reflection law locally and an additional assumption, the photon passes through the opening and changes the direction of its geodesics axis, which creates the light diffraction. Indeed:

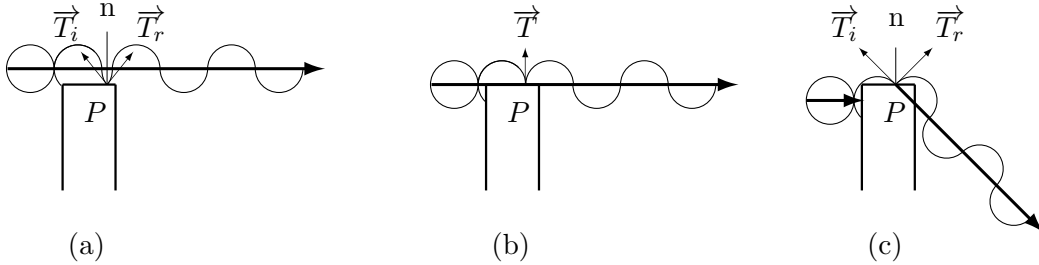


Figure 6: Illustration of one geodesics deviation with respect to the barrier of width l .

i) for the case (a) Fig.5, the lower part of the infinity of geodesics (6), that encounters the vertical interface orthogonal to the geodesics axis, is obstructed (reflected by the vertical side of the barrier) and the photon near the corner has only the possibility to travel with the upper geodesics and the part of geodesics that does not encounter the vertical interface. If the photon follows one of the geodesics that do not cross the vertical interface, and encounters the horizontal side of the barrier of width l at the point of incidence P (see (a), for one geodesic Fig.6), it will be locally reflected following the laws of reflection (the tangent line with unit vector \vec{T}_i of the photon's incident path and the tangent line with the unit vector \vec{T}_r of the photon's reflected path at the point of incidence P are symmetric with respect to the normal line n that passes through the point of incidence P). When the photon is reflected, following the chosen path, it crosses the incident geodesics axis and undergoes a displacement

that follows it. The local reflection (on the horizontal side of the barrier) changes only the antipodal points and conserves the overall displacement direction determined by the geodesics axis (only the upper geodesics and the part of geodesics that does not encounter the vertical barrier side pass through without any change in the incident geodesics axis).

ii) for the case (b) Fig.5, the lower part of the infinity of geodesics (6), that encounters the vertical interface, is obstructed (reflected by the vertical side of the barrier) and the photon near the corner has only the possibility to travel with the upper geodesics. When the photon, by following the geodesics, encounters the horizontal side of the barrier of width l (see (b), Fig.6) at the point of incidence P , it will be locally reflected following the laws of reflection (the tangent line of unit vector \vec{T}_i of the photon's incident path is vertical as well as the tangent line of unit vector \vec{T}_r of the photon's reflected path at the point of incidence P) and undergoes a displacement that follows the incident geodesics axis. The local reflection on the horizontal barrier side of width l does not change the antipodal points of the geodesics and conserves the overall displacement direction determined by the geodesics axis (only the upper part of the geodesics passes through without any change in the incident geodesics axis).

iii) for the case (c) Fig.5, the lower part of the infinity of geodesics (6), that encounters the vertical interface, is obstructed (reflected by the vertical side of the barrier) as well as a part of the upper geodesics. The photon near the corner has only the possibility to travel with the upper geodesics that do not encounter the barrier. When the photon, by following the geodesics, encounters the horizontal side of the barrier of width l (see (c), Fig.6) at the point of incidence P , it will be locally reflected following the laws of reflection (the tangent line of unit vector \vec{T}_i of the photon's incident path and the tangent line of the unit vector \vec{T}_r of the photon's reflected path at the point of incidence P are symmetric with respect to the normal line that passes through the point of incidence P) and undergoes a displacement that follows a constructed geodesics axis (by considering the point of incidence P as a starting antipodal point for a new geodesic direction since it does not encounter neither obstacle nor the incident geodesics axis) perpendicular to the tangent vector \vec{T}_r on the point of incidence P . The local reflection on the horizontal barrier side of width l changes the antipodal points of the geodesics and deviates the overall displacement direction by constructing a new geodesics axis that is perpendicular to \vec{T}_r (only the upper part of the geodesics that do not encounter the vertical barrier interface passes through with deviation of the geodesics axis). The deviation of the geodesics axis from horizontal is related to the angle of the tangent vector \vec{T}_r with respect to the normal line at the point of incidence P . Indeed, the farther the incident geodesics axis is from the obstacle corner (down the corner in Fig.7, (a)), the bigger the angle is between the normal line and the tangent vector \vec{T}_r , and the more the new geodesics axis deviates from the horizontal beyond the barrier (such that it remains orthogonal to the reflected tangent vector \vec{T}_r at the point of incidence P). The bigger the obliquity of the tangent \vec{T}_r at the point of incidence P is, the bigger the deviation of the geodesics axis is (see illustration in 2D of geodesics (a), Fig.7).

The deviation of the overall direction (the geodesics axis) of the photon's geodesic beyond the boundary, when the incident geodesics axis is totally obstructed by the vertical side of the barrier meanwhile the photon's geodesic bypasses the vertical side of the barrier and is reflected by the horizontal side of the barrier, is obtained under the assumption that the point of incidence P , in the horizontal side of the barrier of width L , becomes antipodal point for the new geodesic.

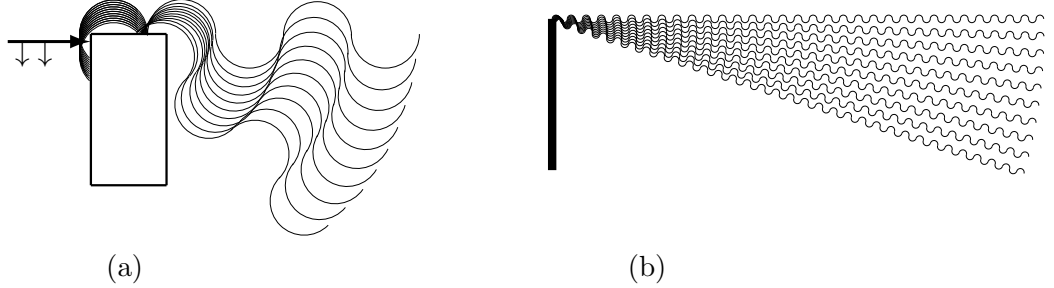


Figure 7: Illustration of photons geodesics axis deviation near the corner of the barrier. (a) The farther the incident geodesics axis is from the corner of the barrier, the bigger the deviation of the reflected geodesics axis is. (b) Illustration of reflection of 10 geodesics defined by (1) with $r = 0.5 \text{ mm}$. The angle of deviation between two successive geodesics axis is $\theta_r = 2^\circ$.

The photon cannot undergo in the direction of the incident geodesics axis since this axis is totally obstructed by the vertical side of the barrier. The geodesics axis represents the overall direction of the photon's geodesics, which is a resultant of a composition of oscillations in the yz -plane and a translation with variable magnitude in the x -axis. The obstruction of the translation in the x -direction induces the deviation of the new photon's geodesic beyond the barrier. The farther the geodesics axis (of the infinity of geodesics given by (6)) is down the barrier's corner, the bigger the geodesics axis deviation is beyond the barrier, the smaller the number of geodesics is, that bypass the vertical side of the barrier and deviate in a new geodesics axis direction. This induces that the light intensity at any point on a given detector screen beyond the slit screen depends on the number of geodesics that bypass the barriers and are reflected by the barrier horizontal side.

The diffraction of the light geodesics is obtained as the photons passe following a part of fluctuating geodesics around the edge of the barrier. The infinity of geodesics reflected by the barrier side of width l creates a new geodesics axis (see illustration of one reflected geodesic (b) Fig.7) and deviates into the region beyond the barrier with an increasing angle until all the light geodesics are totally obstructed by the vertical side of the barrier, which explains the deviation of the light from rectilinear direction.

If photons, by traveling via the infinity of geodesics defined by (6), encounter a barrier that has an opening of dimension $d = 2r$, the part of the geodesics that is not reflected by the vertical edge of the barrier passes through the opening, flares out (diffracts) into the region beyond the barrier, and the flaring is due to the reflection of the photons on the horizontal barrier's edge (see Fig.8). The superimposition of two distant copies, of the diffraction illustrated in (Fig.8), on the same graph, reproduces the interference pattern of fringes visible in the whole intersection region between geodesics, similar to the interference observed in the detector screen of Young's double-slit experiment (see [4]).

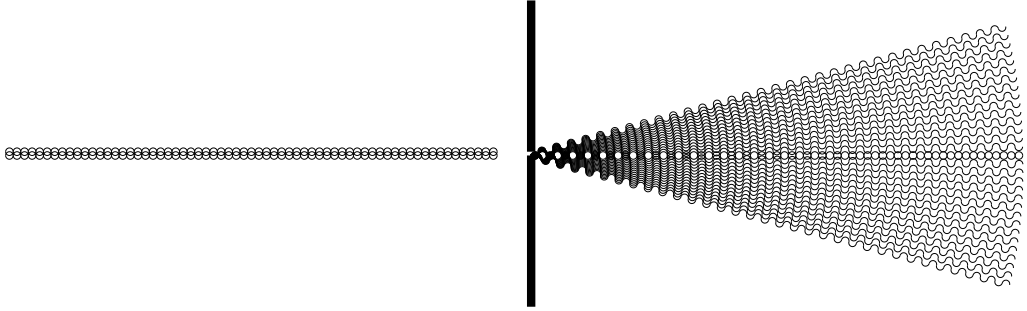


Figure 8: Diffraction of geodesics in 2D. The geodesics radius is $r = 1 \text{ mm}$, the slit's width is $d = 2r$, the angle of rotation of each geodesic is 1° . 15 geodesics are deviated from each edge of the slit. The geodesics reflected by the lower horizontal edge are in anti-phase with the geodesics reflected by the upper horizontal edge.

5 Conclusion

It is known that diffraction arises with all types of wave and its explanation can be found in Huygens' wave theory ([20],[13]) (under the assumption of Huygens-Fresnel principle). Observations of this phenomenon with many other types of physical systems (atoms, electrons, molecules, photons, protons, neutrons) around edges and barriers with slits, are considered as a pure manifestation of wave-like nature of the physical system. It is also known that geometrical optic failed to bring a rational explanation of the deviation of the light ray from rectilinear when it encounters an edge of a barrier or a narrow slit in a screen. This absence of consistent explanation of the light diffraction is maybe due to our misunderstanding of the space-time for the small scale world ([2]), or to our misunderstanding of the real nature of paths of least time for a physical system at the small scale world (quantum scale) that are shaped by the nature of the geodesics of the space-time.

Within this work, we explain the diffraction of light using an infinity of fluctuating geodesics (6) that might be taken by photons in their quest of path of least time that minimizes the needed time to travel between two distant locations in an homogeneous space. The explanation of light diffraction completes the previous interpretation ([4]) of the interference pattern of Young's double-slit experiment. Indeed:

i) if the infinity of geodesics (6) are considered as paths of least time for the physical system in an homogeneous space-time, the use of these fluctuating geodesics for the small scale world (the quantum scale) provides a consistent explanation of the diffraction of light, when it passes through a narrow slit, as a consequence of the reflection of these infinity of fluctuating geodesics on the edge of the narrow slit. This interpretation is consistent with the observed flaring of light when it encounters a narrow slit, and observation of these infinity of geodesics (6) with small radius at the macroscopic scale reveals a straight line geodesic as path of least time.

ii) the superimposition of two copies of diffracted fluctuating geodesics (6) when they passe through a narrow slit reproduces the interference pattern observed in Young's double-

slit experiment, and not only on the detector screen but also on the region between the slits and the detector screen ([4]), which provides a rigorous explanation of the interference pattern without using the wave theory and formalism.

The reproduction of interference pattern using only space-time geodesics reflects the print of the space-time characteristics rather than the real nature of the physical system and puts into question our interpretation of the nature of the physical system as a consequence of the observed diffraction phenomenon, or the observed interference phenomenon. The wave explanation of light diffraction is and remains a good approximation of the phenomenon, but it is not the only one and it is not sustainable as a determinant factor for the physical system nature since diffraction and interference can be explained with paths and trajectories. This new insight makes light particle-like nature conciliable with the so-called interference phenomenon.

References

- [1] Authier A., *3: The Dual Nature of Light. Early Days of X-ray Crystallography*, Oxford University Press, p. 23, 2013.
- [2] Bacry H., *Localizability and Space in Quantum Physics*, Lecture note in physics, Vol. 308, Springer Verlag, 1988.
- [3] Ben Adda F., Porchon H., *Light Fractal Geodesics in an Expanding Space-Time*, arXiv:1302.1490v1, 2013.
- [4] Ben Adda F., *A New Fundamental Factor in the Interpretation of Young's Double-Slit Experiment*, Preprint, 2014.
- [5] Bohr N., *On the Constitution of Atoms and Molecules, Part II Systems Containing Only a Single Nucleus*, Philosophical Magazine 26 (153): 476-502, 1913.
- [6] Compton A.H., *A Quantum Theory of the Scattering of X-Rays by Light Elements*, Physical Review 21 (5): 483-502, 1923.
- [7] Davisson, C.J., *The Diffraction of Electrons by a Crystal of Nickel*, Bell System Tech. J., 7 (1), p 90-105, 1928.
- [8] De Broglie L., *Recherches sur la théorie des quanta*, Thesis, Paris, 1924.
- [9] Descartes R., *Le Monde de Mr Descartes, ou Traité de la lumière et des autres principaux objets des sens*, Paris, 1633.
- [10] Dirac P. A. M., *The Quantum Theory of the Electron*, Proceedings of the Royal Society of London, Series A, 117 (778): 610-24, 1928.
- [11] Einstein A., *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*, Annalen der Physik 17 (6): 132-148, 1905.
- [12] Ekspong G., *The Dual Nature of Light as Reflected in the Nobel Archives*, Proceedings of the American Philosophica, Vol. 143, No. 1, p42, 1999

- [13] Fresnel A.J., *Mémoire sur la diffraction de la lumière*, Mémoires de l'Académie des Sciences (Paris), vol. 5, p 33-475, 1826.
- [14] Fresnel A.J., *Mémoire sur la diffraction de la lumière* , Annales de la Chimie et de Physique, 2nd séries, vol. 1, p 239-281, 1816.
- [15] Glasser O., *Wilhelm Conrad Röntgen and die Geschichte der Röntgenstrahlen*, Berlin, 1931.
- [16] Grimaldi F. M., *Physico mathesis de lumine, coloribus, et iride, aliisque annexis libri duo*, Bologna ("Bonomia"), Italy: Vittorio Bonati, p 1-11, 1665.
- [17] Harrison E., *Interpretation of extragalactic redshifts*, Astrophys. J., 232, 18-19, 1979.
- [18] Hertz H.R. *Über die Ausbreitungsgeschwindigkeit der elektrodynamischen Wirkungen*, Annalen der Physik, vol. 270, no. 7, p. 551-569, 1888.
- [19] Hillebrand, C.D. *Nobel century: a biographical analysis of physics laureates*. Interdisciplinary Science Reviews, 27. 2: 87-93, 2002.
- [20] Huygens C., *Traité de la Lumière*, Leiden, Netherlands: Pieter van der Aa, 1690.
- [21] Ibn al-Haytham A., *Book of Optics*, 1021, Latin translation from the Kitab al-Manazir (Book of Optics), 1572.
- [22] Maxwell J.C., *A Dynamical Theory of the Electromagnetic Field*, Philosophical Transactions of the Royal Society of London 155, 459-512, 1865.
- [23] Newton I., *A Letter of Mr. Isaac Newton containing his New Theory about Light and Colors*, Philosophical Transactions of the Royal Society, No. 80, p 3075-3087, 1671/2.
- [24] Newton I., *Opticks or, a treatise of the reflexions, refractions, inflexions and colours of light...*, Royal society, 1704.
- [25] Planck M., *The theory of heat radiation, second edition*, translated by M. Masius, Blakiston's Son and Co, Philadelphia, p 22, 26, 42, 43, 1914.
- [26] Sabra A.I., *The Optics of Ibn al-Haytham. Books I-II-III: On Direct Vision*, 2 vols, Studies of the Warburg Institute, vol. 40, The Warburg Institute, University of London, 1989.
- [27] Sabra A. I., *The Optics of Ibn al-Haytham. Edition of the Arabic Text of Books IV-V: On Reflection and Images Seen by Reflection*, 2 vols, The National Council for Culture, Arts and Letters, Kuwait, 2002.
- [28] Schrodinger E., *Quantisierung als Eigenwertproblem*, Annalen der Phys, 384 (4): 273-376, 1926.
- [29] Schweber S.S., *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*, Princeton University Press, 1994.
- [30] Thomson G.P., *The Waves of an Electron*, Nature, 122, 279-82, 281, 1928.

- [31] Tomonaga, S.I., *The Story of Spin*, University of Chicago Press, Oka, Takeshi (transl.), 1997.
- [32] Von Laue M., *Röntgenstrahlinterferenzen*, Physikalische Zeitschrift, 14 (22/23): 1075-1079, 1913.
- [33] Young T., *The Bakerian Lecture: On the Theory of Light and Colours*, Philosophical Transactions of the Royal Society of London, 92: 12-48, 1802.
- [34] Young T., *The Bakerian Lecture: On the Theory of Light and Colours*, Philosophical Transactions of the Royal Society of London, 92: 12-48, 1802.
- [35] Young T., *A Course of Lectures on Natural Philosophy and the Mechanical Arts*, London; Printed for J. Johnson, Vol. 1, Lecture 39, p. 463-464, 1807.