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ABSTRACT

This paper investigates the refraction/reflection laws and the double slit interference pattern for particles. We used boundary conditions that consider the discrete and vibrant structure of the matter with which the particles interact, resulting in their scattering, enabling the use of the Huygens and Huygens-Fresnel principles for particles. We managed to obtain results that generalize Snell's law, the reflection law and Young's double slit pattern, for regions very close to the refraction/reflection interface and the slits. The choice made of the scattering used, seems to be the key for a mechanical explanation of light and Young's double slit pattern, including the case of the particles passing through the slit one at a time, therefore, it challenges the validity of the Niels Bohr's complementarity principle and might be the missing link that reconnects without hierarchies both Classical Mechanics and Quantum Mechanics.

Keywords: Huygens-Fresnel Principle; Refraction; Young's double slit pattern; Snell's law; Complementarity Principle.

RESUMO

Nesse trabalho investigamos as leis da refração/reflexão e o padrão de interferência em fenda dupla para partículas. Usamos condições de contorno que consideram a estrutura discreta e vibrante da matéria com a qual as partículas interagem, resultando num espalhamento destas que possibilita o uso dos princípios de Huygens e de Huygens-Fresnel para as partículas. Conseguimos obter resultados que generalizam a lei de Snell, alei da reflexão e o padrão de Young da fenda dupla, para regiões muito próximas da interface refratora/refletora e das fendas. A escolha feita para o potencial de espalhamento utilizado, parece servir de chave para uma explicação mecânica da luz e o padrão de Young da fenda dupla, inclusive no caso da passagem de uma partícula de cada vez pelas fendas, por isso coloca em xeque a validade do princípio da complementariedade de Niels Bohr e pode ser o elo perdido que reconecta sem hierarquias a Mecânica Clássica e a Mecânica Quântica.

Palavras-chave: Princípio de Huygens-Fresnel; refração; padrão de Young da fenda dupla; lei de Snell; princípio da complementariedade.

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RESUMEN

En este trabajo investigamos las leyes de refracción / reflexión y el patrón de interferencia de doble rendija para partículas. Utilizamos condiciones de contorno que consideran la estructura discreta y vibrante de la materia con la que interactúan las partículas, lo que resulta en una dispersión de estas que permite el uso de los principios de Huygens y Huygens-Fresnel para las partículas. Pudimos obtener resultados que generalizan la ley de Snell, la ley de reflexión y el patrón de Young de la doble rendija, para regiones muy cercanas a la interfaz refractora/reflectora y las rendijas. La elección realizada por el potencial de dispersión utilizado parece servir como clave para una explicación mecánica de la luz y el patrón de Young de la doble rendija, incluso en el caso de pasar una partícula a cada vez por las rendijas, por lo que pone en jaque la validez del principio de complementariedad de Niels Bohr y puede ser el eslabón perdido que reconecta la Mecánica Clásica y la Mecánica Cuántica sin jerarquías.

Palabras clave: Principio de Huygens-Fresnel; Refracción; Modelo joven de la doble rendija; La ley de Snell; Principio de complementariedad.

1. INTRODUCTION

Optics phenomena have been studied by physicists for many centuries based on different concepts of the nature of light. The British physicist Isaac Newton (Newton, 1643) (1643-1727), in his *annus mirabilis* proposed that light should be made of particles. The Dutch physicist and mathematician Christian Huygens (1629-1695), in turn, imagined light as made of waves, and that collisions between the ether corpuscles, similar to air molecules, would transmit changes to their neighbourhood propagating light. Based on such ideas, Huygens formulated a principle for the propagation of these waves, currently known as Huygens Principle. Using this principle, Huygens was able to explain the phenomenon of light propagation in a straight line, its reflection and refraction. The French physicist Augustin-Jean Fresnel (1788-1827) presented a mathematical expression for the Huygens Principle for monochromatic waves using spherical waves overlapping. Fresnel's work resulted in a new principle called Huygens-Fresnel Principle, which also explained interference phenomena. The English physician and physicist Thomas Young (1773-1829), considered by many the first scientist to carry out double slit experiments, brought about a demand for the understanding of light that is still rooted in physics. Thomas Young's double slit interference pattern could only be explained up to now by admitting light as a wave. The British physicist James Clerk Maxwell (1831-1879), when manipulating the laws of electromagnetism for electrical and magnetic fields, noticed that they respected a wave equation whose propagation speed would be equal to the speed of light. Maxwell's study results enable the recognition of light as a transversal wave, made of electrical and magnetic fields, that is, an electromagnetic wave. From Maxwell's work onwards, the optics and electromagnetism areas were joined, which made it possible to explore theoretically other phenomena such as polarization and light emission by accelerated electrical charges. The German physicist Max Planck (1858-1947), considered the father of Quantum Physics, suggested that electromagnetic waves should be quantized to create an explanation for the black body radiation emission spectrum. Another German physicist, Albert Einstein (1879-1955), based on Planck's theory, reinforced the understanding that light should be made of particles and proposed the existence of photons to explain the photoelectrical phenomenon. The photon was a special particle whose energy would be linked to an exclusive characteristic of waves that would be its frequency. The Danish physicist Niels Bohr (1855-1962) proposed a model of atom and presented a way to produce photons, through electronic transitions, that is, one electron when “jumping” from an orbital to another would be liable to the emission or absorption of a photon whose energy would be exactly the energy difference between the orbitals. After the works by Planck and Einstein, the French physicist Louis De Broglie (1892-1987) associated a wavelength to the momentum of a particle and the photon would become a particle characterized by the same parameters as those of a wave. With an experimental work that agreed with the De Broglie’ theory, Davison and Germer in their 1927 work on the diffraction of electrons in nickel crystal, contributed to the appearance of the wave-particle duality and a new conception of Quantum Mechanics, involving physicists as Werner Heisenberg (1901-1976), Ervin Schödinger (1887 -1961), Paul Dirac (1902-1984) among others. After a turbulent period regarding the interpretation of experimental results, the Copenhagen Interpretation, as it is known, was considered hegemonic and still holds as an important reference professor Richard Feynman’s (1918-1988) point of view related to the Thomas Young’s double slit interference pattern, published in the collection “Lectures Feynman”. In that context, professor Feynman suggested a mental experiment in which a machine gun would shoot indestructible bullets in random directions towards a metal plate with two holes that were large enough to let the bullets go through them. Then, the bullets might collide or not with the walls of the holes and travel up to a screen where they are counted and show a larger number of bullets concentrated on two positions just behind the two holes. Since this pattern is not the T. Young’s interference pattern, Feynman suggested that:

> *“...it is impossible, absolutely impossible, to be explained in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery.”*

Since then some experimental works use that assertive as a criterion to decide whether something behaves like a wave or like a particle, if the interference pattern occurs, it is considered a wave behavior, if not, it is a particle like behavior. Before professor Feynman, Niels Bohr had added the principle of complementarity to the wave-particle duality, according to which the two behaviour patterns cannot be exhibited at the same time, but not for being contradictory, since they are complementary.

In this study, we investigated the refraction/reflection and double slit interference phenomena, which are the optics conceptual base. The interference phenomenon in the double slit problem was analyzed, in which we built up an alternative to professor Feynman’s reasoning based on the Huygens’ and the Huygens-Fresnel Principles and showed that they are fundamental to explain reflection/refraction and interference phenomena. For our reasoning, we put ourselves in the place of a photon or electron and then asked: What, in that case, we could understand as a double slit? Unlike the bullets colliding with continuous and smooth walls and rebounding when touching them, we noticed that a photon or electron would realize the complexity of the network of atoms that constituted the slit walls. Many atoms in thermal movement, with moving electrons, resulting in electromagnetic fields changing with time, everything in the two walls of a slit, which are too close to allow the interaction with the incident particles going through them to be sufficiently intense. In addition to taking into consideration the details in this interaction with the slit walls, composed of scattering centers in discrete positions, we also observed the requirements of the incident beam organization details, from which at least spatial coherence is required, that is, that the incident particles be disposed in parallel planes to the plane of the wall that contains the slits, separated one from another by the same length, similar to the wavelength of a monochrome wave.

Such reasoning allowed us to access more intuitively the problems analyzed and we found mathematical solutions in smaller dimensions than those we are used to, one example is the double slit case in which we obtained the behaviour of the particle beams too close to the slits, so close that the traditional approximation of two straight angles in a right triangle does not apply. All this should also apply to waves, up to the validity of the principles and hypotheses that we follow. In another example, we found out that the refraction/reflection phenomenon is also described by the same interference phenomenon, generated by the overlap of spherical waves created in the particle scattering of refraction/reflection interfaces.

2. MATHEMATICAL ASPECTS - APPLICATIONS

Our first hypothesis considers that: In the huge number of atoms of the material of which a macroscopic interface is made, even if millimetric, there is a huge number of electrons in constant movement. The electromagnetic field in a certain position is generated by a large number of interface charges, these charges are under the influence of the random nature of thermal effects and a photon or electron in that position must be scattered in random directions, in the sense that we do not know the scattering potential that acts on the particle at a given instant in time.

In his book called "Optics" Eugene Hecht explains that:

> "Generally, we can imagine that in a medium illuminated by an ordinary beam of light; each atom behaves as though it was a "source" of a tremendous number of photons (scattered either elastically or resonantly) that fly off in all directions. A stream of energy like this resembles a classical spherical wave. Thus we imagine an atom (even though it is simplistic to do so) as a point source of spherical electromagnetic waves – provided we keep in mind Einstein's admonition that the "outgoing radiation in the form of spherical waves does not exist. When a given material with no resonances in the visible is bathed in light, nonresonant dispersion occurs, and it gives each participant atom the appearance of being a tiny source of spherical wavelets".

Despite Einstein's warning regarding electrical and magnetic aspects of light, we can think about spherical waves for the location of photons as being a region similar to a spherical shell (spherical surface), where the likelihood to find these photons is different from zero, it dislocates with time and the particle speed.

The second hypothesis that is the invariance of the kinetic energy of scattered particles, which was already reported by Davison and Germer in 1927, more specifically in the summary of the work on their electron diffraction experiment.

> "The distribution in latitude and azimuth has been determined for such scattered electrons as have lost little or none of their incident energy".

3. ANALYSIS OF PARTICULAR CASES

3.1 REFRACTION/REFLECTION

We initially observed that, since we are using the Huygens-Fresnel Principle[2], the results obtained should recover those known for plane waves, obviously, in the limit where the spherical waves have a large enough radius. However, it seems relevant to emphasize that, due to the random character of the location of a particle, as shown in Figure 1, and due to the kinetic energy of that particle being constant after it was scattered, our reasoning ascribes a meaning to the spherical wavefront, which is "the region of no null probability of finding the particle", a moving spherical surface that increases its radius with the same speed as the particle. When several particles are scattered at the same time by the same center, this "wave" front would be full of particles and would be a Huygens's secondary wavefront[3].

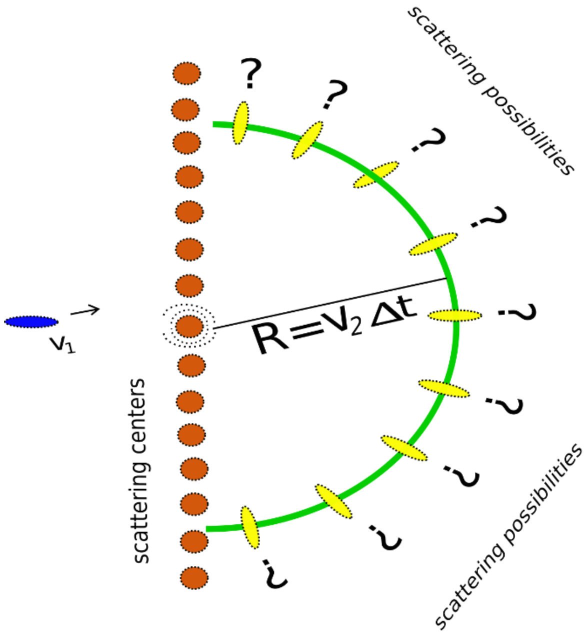

Figure 1 – Scheme of a particle scattering, yellow ellipses show some of the possible locations of the incident particle depicted by the blue ellipse. The brown circles represent the interface scattering centers, after the time interval Δt, the probability region different from zero of finding the particle is represented by the green circumference.

To examine the refraction/reflection phenomenon we will consider a front made of several particles on a plane, this front moves in the normal direction towards the particle plane and will focus on an interface of separation between two dielectric media, located on the vertical axis. Each scattering center of that interface will be responsible for the scattering of a large number of particles at the same time. Figure 2 shows some instants of the evolution of a single particle source, it focuses on the interface of separation between two media (1 and 2), and the incident front is represented by the red dotted line which focuses on an incidence angle with the interface. We considered that scattered front on three distinct scattering center, represented by the orange circle in the vertical axis. This is a problem that might be solved in two dimensions and the "spherical" fronts are circumferences in the page plane that evolve and intersect. We will see that this is one of the most important facts in this study, the overlap!

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[2] [HEC02, p. 444]
[3] [HUY90, p. 22]

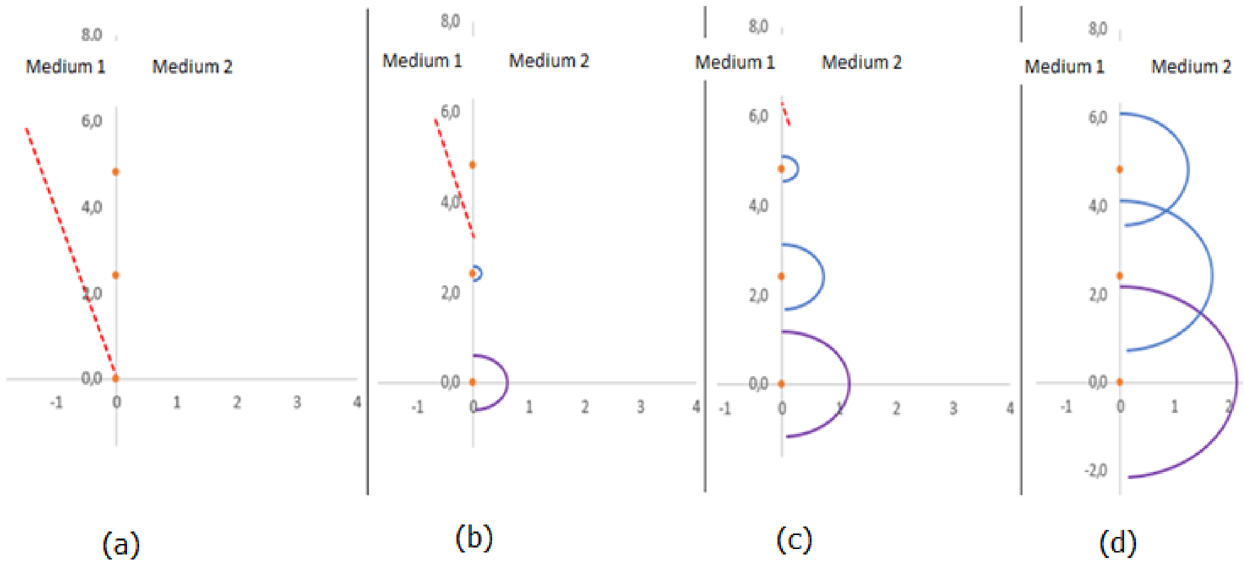

Figure 2 – In (a) a red dotted line dislocates to the right, at a given angle with the horizontal axis and represents the particle front. In (b) the particle front has already touched the interface, in the position of the first scattering center (●) at the origin and a little later, it also touched the second scattering center on the vertical axis, we also have the two wavefronts and the corresponding circular secondary waves. In (c) and (d) these secondary wavefronts evolve and in (d) they already intersect.

In Huygens Principle, the main wavefront, resulting from the scattering of the three centers shown in Figure 2-d, would be the straight line tangent to the three circumferences. According to the Huygens-Fresnel Principle, at each point in space, we would have to calculate the interference of these three waves and for that, in this study, it makes sense to concern with the intersection points only, since at them, we have a single instant in time, that is, twice the probability of finding a particle, and therefore, there is a maximum of interference. In those maxima, the probability intensity, that is, the probability per area unit and per time unit, ends up as the probability per volume unit, or probability density.

It seems relevant to observe that the in the scattering of a front with many particles, over a single scattering center, the particles are distributed over the space in a radial fashion. However, the more scattering centers exist, the more intersections occur and the maxima of interference are the groups of particles. Such intersections are the most intense part of the scattered particle field, these maxima are observed as particle beams and they define the beam propagation direction.

Let's then analyze mathematically the evolution of these maxima of interference on the right hand of the interface, for that purpose, we need the information in Figure 3, there, we see the three time instants being considered and when a particle front touches the scattering centers:

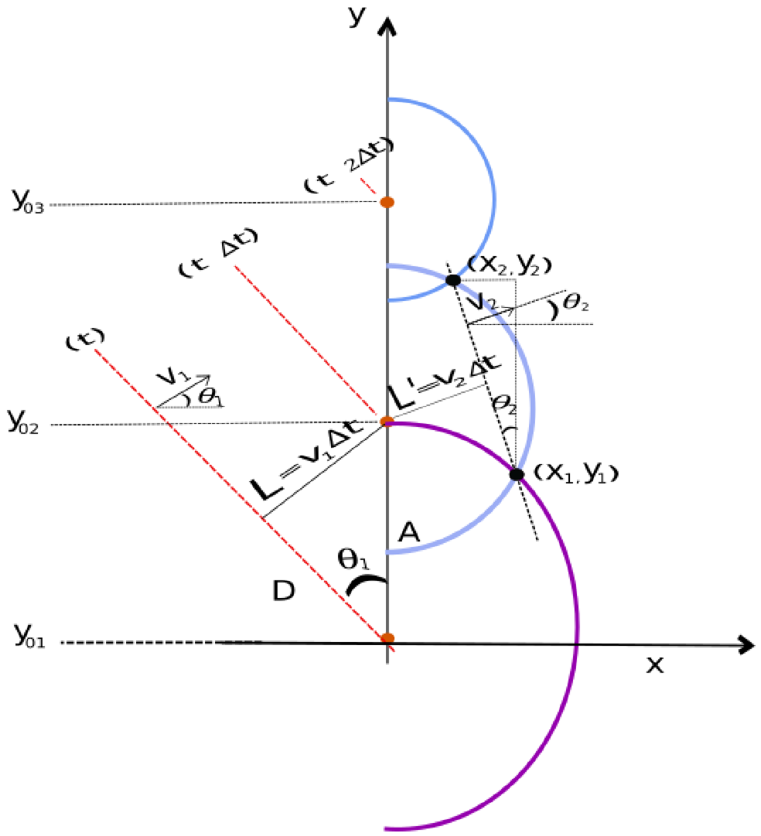

Figure 3 – Scheme representing the formation of three spherical regions (in two dimensions) and their intersections or maxima of interference. The y axis represents the separation interface between the two media (1 and 2), the black circles (●) used to study the maxima are indicated by the points (x_1, y_1) and (x_2, y_2).

First, let's find the position of the maxima, we observed the overlap of two circumferences and these positions are simultaneous solutions for two equations of the circumferences, the first maximum occurs between the first circumference, R_1 radius, and the second R_2 radius, the second maximum occurs between the circumference of R_2 radius and the one of R_3 radius. To obtain the relation between these radii, given in equation (1) we must observe that:

On the left hand of the y axis (medium 1) the velocity of propagation is shown as v_1 and on the right hand (medium 2) as v_2. Therefore, in a time interval Δt, the plane wavefront, on the left hand, will dislocate from L, while the secondary wave, on the right hand, will dislocate from L'. The colored circumferences represent secondary waves generated by the contact of the incident wave with the media separation surface. At the position y_{01} , the first contact occurred, at y_{02}, the second, after Δt, and at y_{03} , and the third, after $2\Delta t$.

In the Δt interval, the first secondary wave travels at a distance R_1, of the medium 2, with modulus velocity v_2. Concerning the plane wave second front, which originates the secondary wave, it travels in medium 1 with modulus velocity v_1, in the interval $\Delta t_1 = \frac{L}{v_1}$, and afterwards in medium 2 with modulus velocity v_2, in the interval Δt_2, requiring $\Delta t_1 + \Delta t_2 = \Delta t$. By analyzing the scheme presented in Figure 1, we could observe that all the other radii R_n are written as a function of R_1 that changes with time, that is:

$$R_n = R_1 - \frac{(n-1)v_2 L}{v_1} \quad , \qquad (1)$$

where $R_1 = v_2\Delta t$ e $n = 1,2,\ldots$ designates the secondary wave; observe that $\frac{v_2 L}{v_1} = L'$.

We could verify that the coordinates (x, y) of a maximum, between two neighboring circumferences n and $n+1$, satisfy simultaneously the two circumference equations, one of radius R_n and another of radius R_{n+1}.

For the first maximum, the equations of the circumferences that these radii must satisfy at the same time are, the first (bottom),

$$x^2 + (y - y_{01})^2 = R_1^2 \qquad , \tag{2}$$

and the second (top),

$$x^2 + (y - y_{02})^2 = R_2^2 \tag{3}$$

By equalling the coordinate x, that is the same for both circumferences, we obtained the coordinate y of the first maximum, $y_{1,2}$:

$$y_{1,2} = \frac{R_1^2 - R_2^2 - y_{01}^2 + y_{02}^2}{2(y_{02} - y_{01})} = \frac{R_1^2 - R_2^2 + A^2}{2A} \tag{4}$$

where, $y_{02} - y_{01} = \sqrt{L^2 + D^2} = A$.

With that, equation (2) gives us the coordinate $x_{1,2}$:

$$x_{1,2} = \sqrt{R_1^2 - (y_{1,2} - y_{01})^2} \tag{5}$$

Likewise, for the second maximum of Figure 3, we have:

$$y_{2,3} = \frac{R_2^2 - R_3^2 - y_{02}^2 + y_{03}^2}{2A} = \frac{R_2^2 - R_3^2 + 4A^2}{2A} \qquad , \tag{6}$$

$$x_{2,3} = \sqrt{R_2^2 - (y_{2,3} - y_{02})^2} \qquad . \tag{7}$$

Similar reasoning takes us to the second pair $(x_{2,3}, y_{2,3}$ and we can generalize these results for the general case:

$$y_{n,n+1} = \frac{R_n^2 - R_{(n+1)}^2 - y_{0n}^2 + y_{0(n+1)}^2}{2(y_{0(n+1)} - y_{0n})} \qquad , \tag{8}$$

$$x_{n,n+1} = \sqrt{R_n^2 - (y_{n,n+1} - y_{0n})^2} \qquad . \tag{9}$$

Figure 4 shows the result of a simulation of the evolution of the maxima of interference as a function of time, a pair of coordinates (x, y) for each time value, the values of the variables involved were: $v_1 = 0{,}4$, $v_2 = 0{,}3$, $\theta_1 = 12{,}4^o$, $y_{01} = 0$, $y_{02} = 2{,}79$, $y_{03} = 5{,}59, L = 0{,}6, A = 1{,}97, \Delta t = 0{,}1$.

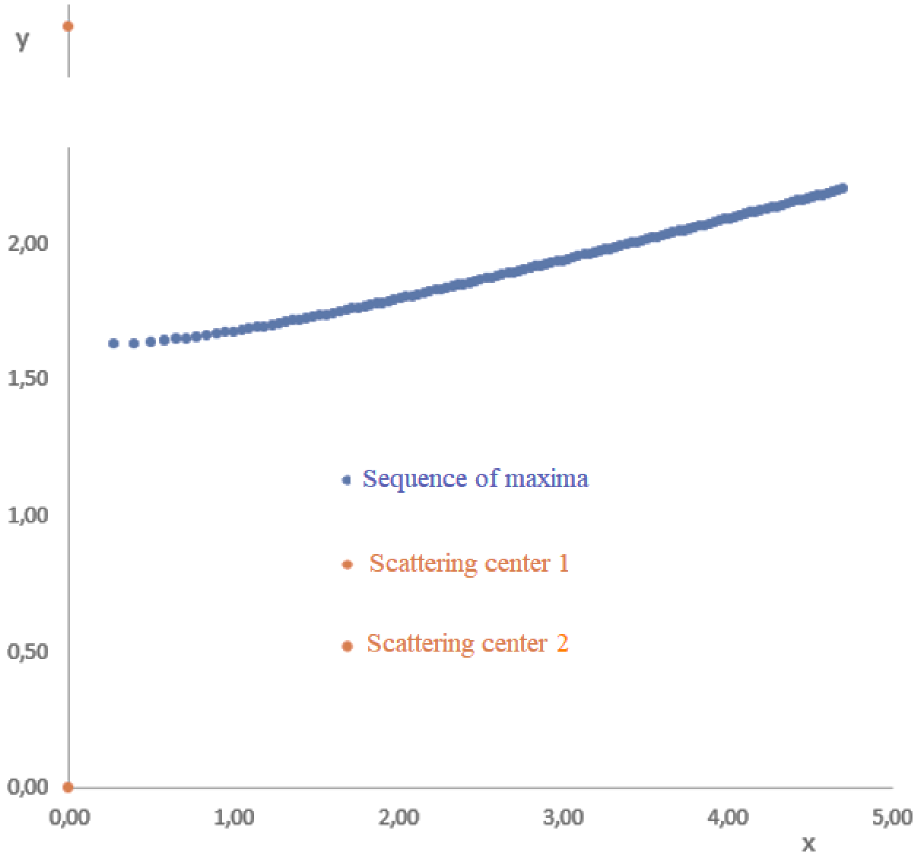

Figure 4 – Sequence of maxima formed by the particle scattering in the two scattering centers represented by the orange circles in the vertical axis.

A time interval between the arrival of the incident particle front and the appearance of the first maximum is observed in Figure 4, that is, the beam of maximums starts to exist from a minimum distance of the interface. In this case, the secondary wavefronts have not intersected yet. It is also interesting to observe that this situation will occur when we have $v_1 < v_2$ and an incidence angle larger than the critical angle, in which the diffracted beam no longer exists, making it geometrically impossible for the secondary wavefront to intersect, photons exist on the right hand of the interface, but they do not group.

We take advantage of this context to examine the curve of the curvature of the beam of maximums close to the interface, since, could we see a curve trajectory for a light beam? According to our model, the light beam bends, but that does not mean that the photons follow the same curve trajectory! After all, a maximum is build up by the geometrical coincidence of photons that move in a straight line from each scattering center, they meet at a maximum position and later on move away from the maxima trajectory.

Now we can investigate the refraction phenomenon, the deviation suffered by an incident beam, when going through an interface that separates two media, with different refraction indices. We obtain the direction of propagation of the beam particles, by the direction of "propagation" of the interference maxima and bear in mind that the refraction law is Snell's law:

$$\frac{sen\theta_1}{v_1} = \frac{sen\theta_2}{v_2} \quad , \tag{10}$$

In Figure 3, we see that v_1 is the velocity of the particle front in the medium 1, v_2 is the velocity of the "spherical" wavefront in the medium 2, θ_1 is the incidence angle and θ_2 is the refraction angle. Also, based on Figure 3, we find the two sides of equation (8), the left hand is obtained directly,

$$v_1 sen\theta_1 = v_1 \frac{L}{A} \quad , \tag{11}$$

while the right hand is obtained from the inclination of the segment of the straight line that united the two maxima:

$$sen\theta_2 = \frac{(x_{1,2}-x_{2,3})}{\sqrt{(y_{1,2}-y_{2,3})^2+(x_{1,2}-x_{2,3})^2}} = \frac{\Delta x}{\sqrt{(\Delta y)^2+(\Delta x)^2}} \quad . \tag{12}$$

The Δy calculation is simpler and results in:

$$\Delta y = y_{2,3} - y_{1,2} = \frac{\left(\frac{v_2 L}{v_1}\right)^2 - A^2}{A} \tag{13}$$

The Δx calculation, carried out in the Appendix, involves a subtraction of square roots and is a little more complicated. The sequence of maxima in Figure 4 shows that the refraction angle changes close to the interface between the media, that is, the value of $sen\theta_2$ given by the equation (12) does not satisfy Snell's law, which admits a single refraction angle θ_2. However, equation (12) recovers Snell's law at the limit in which we can consider $R_1 = v_2 \Delta t$ large enough, in this case, for Δx we have:

$$\Delta x = |x_{1,2} - x_{2,3}| = \frac{v_2}{v_1} L \frac{\sqrt{A^2 - \left(\frac{v_2 L}{v_1}\right)^2}}{A} \quad . \tag{14}$$

Then, far from the interface we have:

$$sen\theta_2 = \frac{\frac{v_2}{v_1} L \frac{\sqrt{A^2-\left(\frac{v_2 L}{v_1}\right)^2}}{A}}{\sqrt{\left[\frac{\left(\frac{v_2 L}{v_1}\right)^2 - A^2}{A}\right]^2 + \left[\frac{-v_2}{v_1} L \frac{\sqrt{A^2-\left(\frac{v_2 L}{v_1}\right)^2}}{A}\right]^2}} \quad , \tag{15}$$

That is, with a little manipulation, we find the asymptotic expression of Equation (12) as:

$$sen\theta_2 = \frac{v_2}{v_1} \frac{L}{A} = \frac{v_2 sen\theta_1}{v_1} \quad , \tag{16}$$

which is the Snell's law given by Equation (10).

As for the reflection, we must consider that the coordinate x of points $(x_{1,2}, y_{1,2})$ and $(x_{2,3}, y_{2,3})$ in Figure 3 must be transformed into $-x$ and also that $v_1 = v_2$, with that, Equation (16) requires $\theta_2 = \theta_1$ since these angles are restricted to the interval $\left(\frac{-\pi}{2}, \frac{\pi}{2}\right)$.

3.2 INTERFERENCE – APPLICATION TO THE DOUBLE SLIT PROBLEM

We will analyze the double slit device, assuming an incident particle front boundary condition as plane and monochromatic and showing length λ between the particle front. When the first particle front depicted as F_1 (Figure 5), which is simultaneously incident upon the slits (normal incidence), two secondary waves f_1^1 and f_1^2 emerge, which are arcs of a circumference with a single intersection point (central maximum). However, when the second wavefront, F_2, is considered, which produces other two secondary wavefronts f_2^1 and f_2^2, intersection points with the first secondary waves will also exist, and such points are the secondary interference maxima.

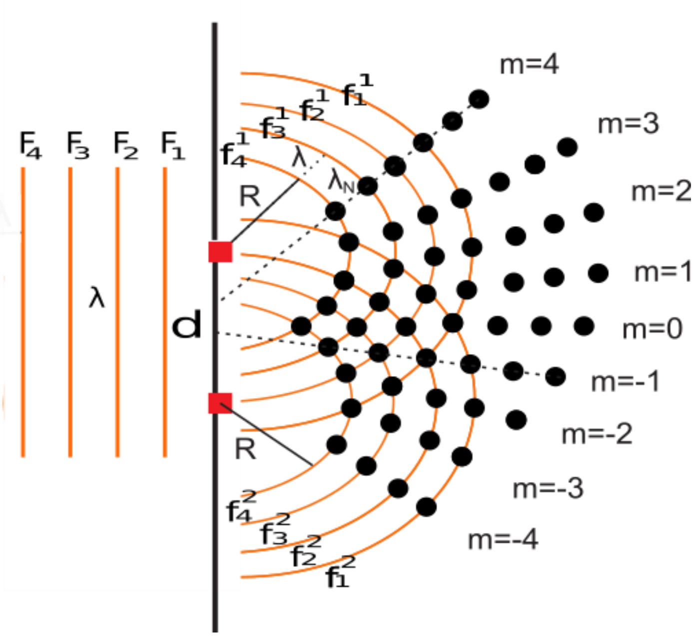

Figure 5 - Incident wavefront $F_1, F_2, F_3, F_4$and four secondary waves $f_1^1, f_2^1, f_3^1, f_4^1$ generated by the top slit (▪) and $f_1^2, f_2^2, f_3^2, f_4^2$ by the bottom slit (▪), maxima (●) are also shown.

Mathematically, we can think about two incident plane wavefront, separated by λ, producing secondary wavefronts separated by λ, since we have the same propagation velocity before and after the slits. Thus a secondary wavefront with radius R can be used as a reference for the radius of the umpteenth secondary wavefront with radius $R_n = R + n\lambda$, with $n = 0,1,2 \ldots$.
Assuming that the slits are located on the y axis, in the positions $y_{01} = 0$ and $y_{02} \neq 0$, the equations of the circumferences, which represent secondary waves from slit 2 and slit 1 (Figure 5), will be:

$$x_2^2 + (y_2 - y_{02})^2 = (R + n_2\lambda)^2 \quad , \quad (17)$$

$$x_1^2 + y_1^2 = (R + n_1\lambda)^2 \quad , \quad (18)$$

where $n_{1,2} = 0,1,2,3 \ldots$ represent the indices of the secondary waves generated by slit 1 located in y_{01}, and by slit 2, located in y_{02}.

In the intersection of these two circumferences, we have $x_1 = x_2 = x$ and $y_1 = y_2 = y$, so that, by solving the system of equations (17) and (18), we obtain the maxima coordinates:

$$y = \frac{y_{02}^2 + (R + n_1\lambda)^2 - (R + n_2\lambda)^2}{2y_{02}} \quad , \quad (19)$$

and,

$$x = \sqrt{(R + n_1\lambda)^2 - y^2}\ . \tag{20}$$

The coordinates of the maxima are found as a function of integer numbers n_1 and n_2. For example, the central maxima appear in $n_1 = 0$ and $n_2 = 0$, that is, in $x = \sqrt{R^2 - \frac{{y_{02}}^2}{4}} \wedge y = \frac{y_{02}}{2}$, and, for each R value, there is a central crossing.

At this point, we could observe that when considering only two scattering centers, equations (8) and (9) with $v_1 = v_2$ e $\theta_1 = 0$ would give us the central maximum coordinates, that is, the phenomenon that occurs at the double slit is the same that occurs in the refraction, interference!

To observe the behavior of secondary waves and maxima, we created a simulation in which four secondary waves were generated to each slit, with radii $R_i = R + i\lambda$ $(i = 0{,}1{,}2{,}3)$, in which we could vary R, as shown in Figure 5. The intersection point coordinates were also calculated, given by equations (19) and (20), for different values of $n_1$and n_2. When R varies, we have the maxima behavior in any desired position, that is, close to the slits or far from them.

Figure 5 shows the existence of points $x(n_1, n_2)$ and $y(n_1, n_2)$ which are part of the same straight line or maxima sequence. Two examples of maxima beams are shown by the dotted lines. The values used for the distance between the slits y_{02} and for λ were $y_{02} = 5{,}7$ and $\lambda = 1{,}1$.

Equations (19) and (20) with $n_2 = n_1 + m$ can be used to obtain the points that make up the same maxima sequence, that is:

$$y_{n_1,m}(R) = \frac{y_{02}}{2} - \frac{m\lambda[m\lambda + 2(R + n_1\lambda)]}{2y_{02}} \tag{21}$$

$$x_{n_1,m}(R) = \sqrt{(R + n_1\lambda)^2 - \left(y_{n_1,m}\right)^2} \tag{22}$$

The values of n_1 and n_2 characterize a maximum and are separated by m, that is, for a given maximum, the two secondary waves that make it up show indices separated by m, and then, all the subsequent maxima, due to the secondary waves separated by the same m, will be part of the same sequence. Thus we concluded that for $m = -1$ we have the maxima $(n_1, n_1 - 1)$ that can take the values $(1{,}0), (2{,}1), (3{,}2) \ldots$

The $sen\theta$ of each sequence (Figure 5) can be calculated by:

$$sen\theta = \frac{\Delta y}{\sqrt{\Delta x^2 + \Delta y^2}}\ . \tag{23}$$

Away from the slits, in neighboring secondary wavefronts, that is, the closest possible, $\sqrt{\Delta x^2 + \Delta y^2} = \lambda_N \approx \lambda$. So that, we have:

$$sen\theta = \frac{y_{n_1,m} - y_{(n_1+1),m}}{\lambda}\ . \tag{24}$$

By using $y_{02} = d$ in equation (21) we obtained $\Delta y = y_{n_1,m} - y_{(n_1+1),m} = \frac{m\lambda^2}{d}$ and, finally, we obtained the famous equation that depicts Thomas Young's double slit interference pattern:

$$dsen\theta = m\lambda \quad . \tag{25}$$

Similarly to the case of the critical angle in refraction, in the double slit there is a limit to be respected so that the secondary maxima exist, which is $\lambda < d$. Figure 6 shows the case in which $\lambda = d = \lambda_c$ and there is only a central maximum.

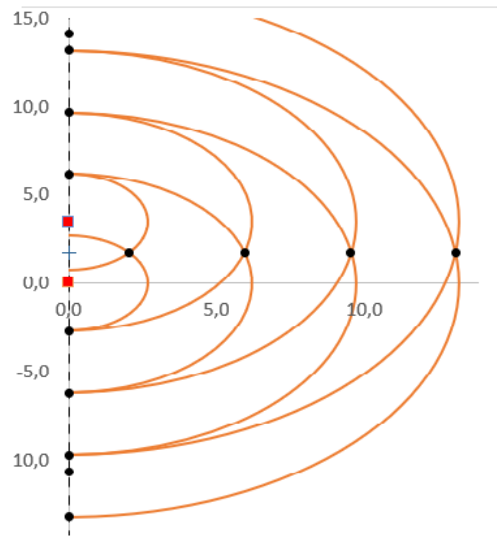

Figure 6 – Similar case to that in Figure 5, in which $\lambda = d = \lambda_c$, only the central maximum is possible.

4. ANALYSIS OF SECONDARY WAVEFRONT OVERLAPPING

Now, we can analyze in more detail the secondary wavefront overlapping, let's use the example of overlap of the two secondary waves, Figure 7, and observe the intensity of the probability density, or particles that reach a certain point.

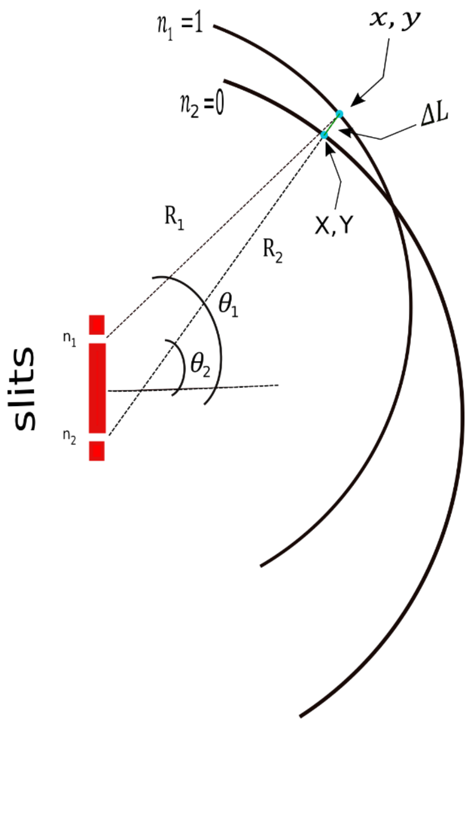

Figure 7 – Double slit scheme for the analysis of the interference maxima intensity, two "spherical" wasvefronts are represented, the maximum intensity value is found exactly where they intersect and it extends to both sides, reducing ΔL and intensity.

Let's say that a number N_0 of particles reach a slit, then the particle density on half of the circumference of the radius $R + n_i\lambda$, emitted by that slit is given by:

$$\rho_i(x, y) = \frac{N_0}{\pi(R+n_i\lambda)} \qquad , \tag{26}$$

we should bear in mind that $n_i = 0,1,2 \ldots$ designating the secondary wavefront "generated" by one of the slits.

Therefore, the number of particles contained in an angle interval $\Delta\theta$ observed from the mean distance between the slits is given by:

$$N_{i,j} = \rho_i(x, y)(R + n_i\lambda)\Delta\theta \qquad , \tag{27}$$

where $j = 1,2$ defines the slits, in which 1 is the bottom one and 2 is the top one, $i = 1,2 \ldots$ designating the wavefront emitted by slit j.

$$N_{i,1} + N_{i,2} = [\rho_1(x, y)(R + n_1\lambda)\Delta\theta + \rho_2(x, y)(R + n_2\lambda)\Delta\theta] \quad . \tag{28}$$

Now we can analyze the intensity of the particles that reach $\Delta\theta$ in a time interval Δt, that is:

$$I = \frac{N}{(R+n_i\lambda)\Delta\theta\Delta t} \qquad , \qquad 29)$$

where $(R + n_i\lambda)\Delta\theta$ corresponds to the "area" element contained in $\Delta\theta$. Observing that the particle velocity is v and that $\Delta t = \frac{\Delta L}{v}$ we substitute (28) with (29) and obtain,

$$I = \frac{v}{\Delta L}\left[\frac{N_0(R+n_1\lambda)}{\pi(R+n_1\lambda)^2} + \frac{N_0(R+n_2\lambda)}{\pi(R+n_2\lambda)^2}\right] \qquad . \tag{30}$$

Then, we have to find ΔL to obtain I, in Figure 7, we notice that:

$$\Delta L = \sqrt{(X - x)^2 + (Y - y)^2} \qquad . \tag{31}$$

However, this amount in the exact position of the intensity maximum becomes null making the intensity infinite, this occurs because up to this point we have not ascribed our particles any size, thus, in order to be more realistic in our analysis, we will ascribe the same diameter δ to our particles and with that, equation (31) becomes:

$$\Delta L = \sqrt{(X - x)^2 + (Y - y)^2 + \delta} \qquad , \tag{32}$$

That is, exactly in the position that locates an intensity maximum $\Delta L = \delta$. To calculate ΔL , we must remember that the circumference equations are:

$$x^2 + (y - y_{02})^2 = (R + n_1\lambda)^2 \qquad , \tag{33}$$

$$X^2 + Y^2 = (R + n_2\lambda)^2 \quad . \tag{34}$$

When choosing a y value as in Figure 7, the corresponding x value is given by,

$$x = \sqrt{(R + n_1\lambda)^2 - (y - y_{02})^2} \quad , \tag{35}$$

the Y value can be found for the linear relation between the points $(x, y)$and (X, Y), that is:

$$\frac{Y}{X} = \frac{y}{x} \quad , \tag{36}$$

So, with (34) and (36) we obtain,

$$Y = \frac{(R+n_2\lambda)(y/x)}{\sqrt{1+(y/x)^2}} \quad , \tag{37}$$

which substituted in (34) gives us the expression for X:

$$X = \frac{(R+n_2\lambda)}{\sqrt{1+(y/x)^2}} \tag{38}$$

Finally, we obtain $\Delta L(y)$,

$$\Delta L = \sqrt{\left(\frac{R+n_2\lambda}{\sqrt{1+(y/x)^2}} - \sqrt{(R + n_1\lambda)^2 - (y - y_{02})^2}\right)^2 + \left(\frac{(R+n_2\lambda)y/x}{\sqrt{1+(y/x)^2}} - y\right)^2} + \delta \tag{39}$$

And also the I intensity:

$$I(y) = \frac{v\left[\frac{N_0}{\pi(R+n_1\lambda)} + \frac{N_0}{\pi(R+n_2\lambda)}\right]}{\Delta L} \tag{40}$$

The $I(y)$ function, for the five maxima $m = 0, \pm 1, \pm 2$, is shown in Figure 8 for the values $R = 115{,}50$, $\lambda = 0{,}5$, $d = y_{02} = 1$, $N_0 = 2$, and $v = 0{,}3$. The different color points represent the maxima exact position were necessary to be included to locate the limit that the different color curves should reach, since y not always increase, in this case equal to 0.5, close to a maximum, captures that limit.

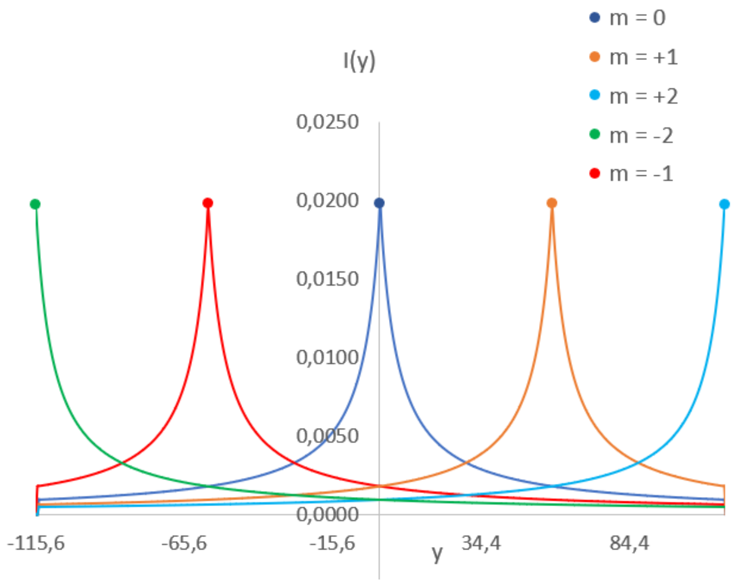

Figure 8 – Five $I(y)$ different color curves for the five maxima given by the pairs $(n_1, n_2) = (0{,}0), (1{,}0), (0{,}1), (2{,}0), (0{,}2)$, the maxima in this case occur exactly in the traditional positions.

We could also notice that there is an overlap of maxima, when Figure 9 is analyzed, we see that a secondary wavefront might belong to more than a maximum, for example, the photons of a maximum that are the last to reach a certain position, will be the first photons of another maximum. Figure 9 shows the photons in the blue line between the red and green regions.

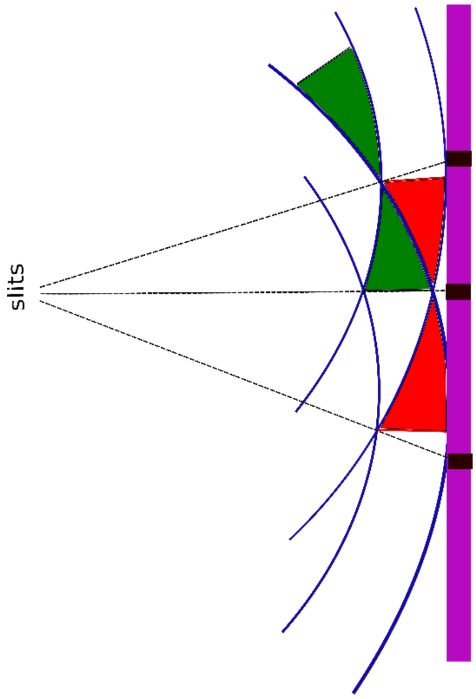

Figure 9 – Common region to the two maxima represented by the colors red and green.

The sum of intensities in Figure 8 is shown in Figure 10.

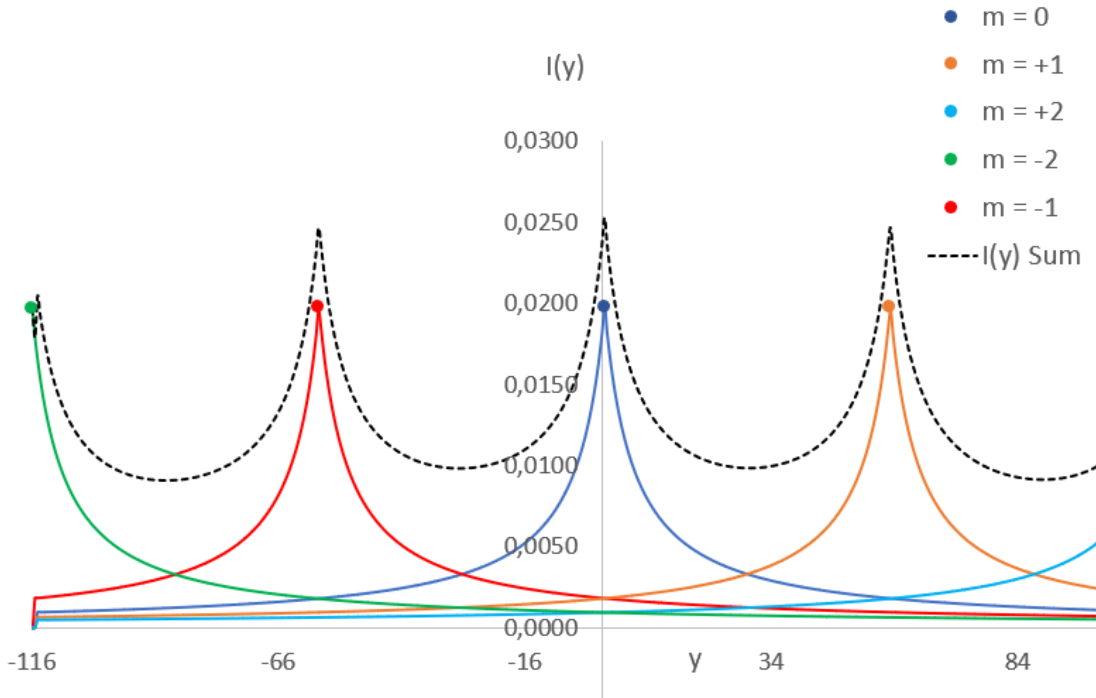

Figure 10 – The dashed line represents the sum of intensities of the two slits.

5. CASE DISCUSSION: PARTICLE ONE TO ONE

As we have already mentioned, the particles reach the slits in a straight line, they are deviated by the slits and then travel again in a straight line as free particles. In Figure 11, we depict three situations in which only two particles reach the slits, a slightly intense beam, which might represent the occurrence of a central maximum with $m = 0$, and two secondary maxima with $m = -1$ and $m = 1$. In the first situation, the two particles reach the two slits at the same time, one at each slit, then, they meet at the only point possible at the backstop, the only place where the two ways have the same length, which is at the central maximum. Bellow, in Figure 11, the other two possibilities for the first secondary maximum are represented, the two particles reach the slits at the same time, but, separated by a distance λ, in this case, a possible meeting at the backstop can only occur in the secondary maximum m=-1 and m=+1.

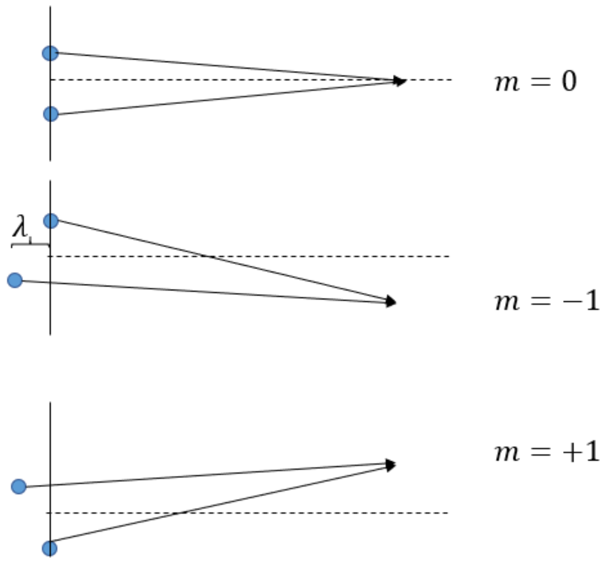

Figure 11 – Pulse made of 2 particles represented by the blue circles and the three possibilities of them constituting a maximum.

In the case of a single particle going through the slits at each time, the central maximum cannot occur, this would then be the criterion to state that one particle at a time is going through the slits.

6. RESULT ANALYSIS

We found a way to apply the Huygens and Huygens-Fresnel Principles to particle scattering, by suggesting, respectively, the "random" particle scattering and an interference maximum where these particles group. With these hypotheses, we examined the cases of particles organized in an incident beam on a refracting/reflecting interface, constituted by scattering centers discretely organized in space, as a result, we recovered Snell's law and showed that it is not obeyed very close to the interface, and that the maxima follow the directions given by equations (8) and (9). We also examined the incidence of organized beams on a double slit, as a result, we recovered Young's pattern and showed that it is not followed very close to the slits, the beams that emerge from the interface or from the slits, seem to originate from a point that is at a certain distance from them. The explanation is that the secondary waves, which originate from scattering centers distant one from another, only intersect after they have travelled a certain distance. Far from the scattering center, the absence of maxima might also occur, we observed that, if for any reason the secondary waves do not manage to intersect, then there are no maxima, and the phenomenon that depends on the existence of these maxima cannot be noticed. This behaviour occurred in relation to the refraction, in which above the critical angle there are no maxima, and also in relation to the double slit, where the wavelength must be smaller than the distance between the slits so that different maxima occur in the central maximum.

It seems relevant to mention that in the double slit, except for the central maximum, in the position of a maximum at the backstop, the secondary wavefronts of the two slits that originated from distinct incident plane waves reach that position at the same instant in time, that is, the secondary waves leave the slits at different instants in time, but can arrive at the same time at special points in the backstop. This explains the maxima intensity in Figure 10, even in the case of one particle at a time passing through the slits.

We presented a model for optics basic phenomena, which is based on a slightly different interpretation of two cases, the Huygens Principle and the Huygens-Fresnel Principle. In the first case we used Albert Einstein's "more realistic" strategy, in an attempt to be more realistic regarding what a photon or another particle would realize when going through an interface between two media, or slits. We then noticed that for a random scattering we would obtain perfectly the production of a Huygens's "secondary wave", which would bring about the meaning desired by the quantum mechanics, of a probability density wave.

In the second case, we proposed the location of an interference maximum exactly in the intersection position between two of these new secondary waves, which allowed us to treat the maxima mathematically in a reasonably simpler way. With that, we could explain as the same phenomenon both the refraction/reflection and the double slit interference, in a broader way. This broader approach enabled us to generalize Snell's law and Young's double slit pattern, in addition to posing a query regarding the validity of the Niels Bohr's Complementarity Principle, when Young's pattern was recovered and in the case of the particles going through the slit one at a time, since we could explain Young's pattern with both descriptions, wave and particles.

7. FINAL REMARKS

In this study, we filled a gap left by the physicists between the boundary conditions traditionally used in the optics problems addressed. We showed that this gap seems to contain the region where the "magic" takes place, in which we clarified what might happen in a double slit, which has been considered a relevant "mystery" in physics for a long time. Basically, if our hypothesis of "random" scattering is right, both Huygens and Huygens-Fresnel Principles should attempt to clarify the "mystery". After all, this random potential makes a lot of sense when we think that the double slit experiment was developed for photons, electrons, neutrons and even atoms, and the same pattern was always obtained, that is, what potential is common to all these particles? What particular potential is that? Is that the particular case of the "random" potential?

In addition, due to the relevance of results, we should consider that the perceived reality through light might be a reality resulting from photon grouping, not only individual photons, but the reality as the result of a collective interference.

The boundary conditions used ended up suggesting an optics explained by the laws of mechanics.

It seems relevant to mention that some experimental works address the double slit case, considering that one particle goes through the slit at a time and even so the central maximum is present in the interference pattern. This places us at a point where we have two options: 1) to accept the experimental results and the criteria used to state that a particle is sent each time, and that a particle is detected at each time, with the extreme accuracy needed, since, taking our study into consideration, if two particles go through the slits at the same time, the central maximum becomes possible, which would confirm the current interpretation of the wave-particle duality; or 2) review these criteria and improve them by redoing the experiments with the necessary safety to state that the particles are sent one after the other and go through the slits one after the other.

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8. REFERENCES

[HEC02] HECHT, EUGENE. **Optics**: São Francisco: Pearson Education, 2002.

[DAV27] DAVISSON, C., GERMER, L. H. Diffraction of electrons by a crystal of nickel. **Physical Review,** vol 30 n. 06, 705 – 741 p, December 1927.

[HUY90] HUYGENS, CHRISTIAAN. **Treatise on Light**: N. York (Leyden): Dover, 1690.

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APPENDIX

Our objective in this appendix is to obtain the term given in equation (12) of the main text, that is,

$$|\Delta x| = \left|x_{1,2} - x_{2,3}\right| \quad . \tag{A1}$$

Now, we use equations (4) and (6) in equations (5) and (7) and obtain,

$$x_{1,2} = \sqrt{{R_1}^2 - \left[y_{1,2}\right]^2} \quad , \tag{A2}$$

$$x_{2,3} = \sqrt{(R_1 - L')^2 - \left(y_{1,2} + \frac{A^2 - {L'}^2}{A} - A\right)^2} \quad . \tag{A3}$$

We work a little on the expression for $x_{2,3}$, in which we identify the first term as,

$$(R_1 - L')^2 = {R_1}^2 - 2L'R_1 + {L'}^2 \quad , \tag{A4}$$

And the second term as,

$$\left(y_{1,2} + \frac{{L'}^2 - 3A^2}{A}\right)^2 = \left[y_{1,2}\right]^2 + 2\left(\frac{-{L'}^2}{A}\right)y_{1,2} + \left(\frac{-{L'}^2}{A}\right)^2 \quad . \tag{A5}$$

Then we evidenced the term $x_{1,2}$ in (A3):

$$x_{2,3} = x_{1,2}\sqrt{1 + \frac{{L'}^2 - 2L'R_1 - 2\left(\frac{-{L'}^2}{A}\right)y_{1,2} - \left(\frac{-{L'}^2}{A}\right)^2}{{R_1}^2 - \left[y_{1,2}\right]^2}} \, . \tag{A6}$$

Now we can show $y_{1,2}$ and use the binomial expansion by finding:

$$x_{2,3} = x_{1,2} + \frac{{L'}^2 - 2L'(R_1) - 2\left(\frac{-{L'}^2}{A}\right)\left[\frac{2L'R_1 - {L'}^2 + A^2}{2A}\right] - \left(\frac{-{L'}^2}{A}\right)^2}{\frac{1}{A}\sqrt{4{R_1}^2A^2 - \left[2R_1(L') - {L'}^2 + A^2\right]^2}} . \tag{A7}$$

Far from the interface, the dominant terms are of the order $O(R_1^2)$ and we can abandon lower order terms, therefore, we obtain:

$$\Delta x = \frac{-L'A + \frac{1}{A}\left(L'^2\right)(L')}{\sqrt{A^2-(L')^2}} \quad , \tag{A8}$$

or even,

$$\Delta x = -L' \frac{\sqrt{A^2-L'^2}}{A} \quad . \tag{A9}$$

The refraction index n will be found by relating the sine of the incidence angle θ_1 with the sine of the refraction angle θ_2, remembering equation (10):

$$\frac{sen\theta_1}{v_1} = \frac{sen\theta_2}{v_2} \quad . \tag{A10}$$

The, we have to identify in equation (12), rewritten as (A11), the term $sen\theta_1 = \frac{L}{\sqrt{L^2+D^2}}$:

$$sen\theta_2 = \frac{|\Delta \boldsymbol{x}|}{\sqrt{\Delta \boldsymbol{x}^2 + \Delta \boldsymbol{y}^2}} \quad , \tag{A11}$$

and for that, we have to remember that $A = \sqrt{L^2 + D^2}$ e que $L' = \frac{v_2 L}{v_1}$, thus, with equations (A9) and (13) we find:

$$\Delta x^2 + \Delta y^2 = -L'^2 + A^2 + 2L'\lambda' \quad . \tag{A14}$$

Equation (A11) becomes:

$$sen\theta_2 = \frac{v_2 L}{v_1\sqrt{L^2+D^2}} \quad . \tag{A15}$$

That is, we obtain equation (A10).