**Quantum operator for non-paraxial single photon interference**

**Operador cuántico para la interferencia no-paraxial con fotones individuales**

**Título corto: Quantum interference operator**

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**Abstract:**

In optics, interference has been described as a result of the superposition of light waves in ordinary space. However, this phenomenological description does not seem to fit non-paraxial single photon interference in ordinary space, due to photon corpuscular nature and that only one photon moves in the setup at each time. A quantum interference operator, deduced from the exact (non-paraxial) mathematical model, indicates that the spatial morphology of interference is independent of the presence of photons in the setup and remains unchanged in their absence. This suggests a new interference interpretation in terms of the photon confinement in geometric states of ordinary space. Physical and phenomenological implications of this new interference interpretation are discussed.

**Keywords:** states of space; geometric potential; confinement; spatially structured wells; vacuum; interference operator.

**Resumen:**

En óptica, la interferencia se ha descrito como resultado de la superposición de ondas de luz en el espacio ordinario. Sin embargo, esta descripción fenomenológica no parece ajustarse a la interferencia no-paraxial con fotones individuales en el espacio ordinario, debido a la naturaleza corpuscular de los fotones y a que solo un fotón se mueve en la configuración en cada momento. Un operador cuántico de interferencia, deducido del modelo matemático exacto (no-paraxial), indica que la morfología espacial de la interferencia es independiente de la presencia de fotones en la configuración y permanece inalterada en su ausencia. Esto sugiere una nueva interpretación de la interferencia en términos del confinamiento de fotones en estados geométricos del espacio ordinario. Se discuten las implicaciones físicas y fenomenológicas de esta nueva interpretación de la interferencia.

**Palabras clave:** estados del espacio; potencial geométrico; confinamiento; pozos espacialmente estructurados; vacío; operador de interferencia.

1. **INTRODUCTION**

Single photon interference has been of fundamental importance in quantum optics and photonics (**De Martini et al,** 1994), (**Shih,** 2021). It has played a crucial role in analysis of quantum properties of light (**Hessmo et al,** 2003), (**Jones & Wiseman,** 2011), basic quantum phenomena (**Rueckne & Peidle,** 2013), (**Tang & Hu,** 2022), and technology development (**Mérolla et al,** 1999), (**Witkoskie & Cao,** 2008). Because of this wide range of uses and applications, single photon interference is also considered paradigmatic in education (**Rueckne & Titcomb,** 1996), (**Marshman & Singh,**2017).

The standard quantum formalism predicts experimental outcomes of paraxial approximated single photon interference. However, it is not suitable for non-paraxial interference and its phenomenological description does not seem to fit the photon corpuscular nature in ordinary space and the fact that only one photon moves in the setup in each individual experimental realization This theoretical term denotes the experimental segment that begins with the emission of a single photon at the source and ends with its annihilation by the detector, in such a way that only this photon propagates in the interferometer without explicit connections with preceding and posterior photons. Consequently, single photon interference experiments can be theoretically characterized as a binary sequence of only-one-particle systems separated by zero-particle systems.

In the following, an alternative description is proposed for the community discussion. It is developed in the framework of a recently reported non-paraxial quantum formalism of interference with light and single matter particles (**Castañeda et al,** 2023). This new formalism is compatible with the photon corpuscular nature, and considers ordinary space as a system with geometric states that confine single photons in spatially distributed zones. A quantum interference operator is deduced in section 2, which includes density operators of the geometric states of space, as shown in section 3. Characterization of Preparation-and-Measurement (P&M) configured interferometers in terms of geometric states of space is discussed in section 4, and section 5 describes the phenomenology of individual experimental realizations in single photon interference. Conclusions are summarized in section 6. Details of the mathematical model can be found in the supplementary information.

1. **QUANTUM INTERFERENCE OPERATOR**

It is shown (see Supplementary Information for details) that the non-paraxial Hamiltonian for the electromagnetic field of single photons takes the form

, (1)

with  ( is Planck constant),  the photon frequency and  the number operator. It is assumed that single photons propagate between two consecutive planes M and D, at a distance  (see Fig. 1 of Supplementary Information). Reduced coordinates  and  denote pairs of points at M and D respectively, with the coordinate suffixed A specifying the midpoint between the pair and the coordinate suffixed D denoting their separation vector. For null separation vectors, the reduced coordinates denote single points. Furthermore,

 (2)

with  and  the complex amplitude of probability for single photons at M;  and  the complex transmission function at M;  and  the unit photon polarization vector at M. The angles  and  are depicted in Fig. 2 of Supplementary Information. Finally (**Castañeda et al,** 2020),

, (3)

with  and  the light speed in vacuum, is a non-local, non-paraxial basis, where  are functions of the Hilbert space corresponding to the coordinate representation of kets , which are labelled for each point of M. Therefore,  is the coordinate representation of the operator , labelled for specific pairs of points at M, i.e. . It is apparent that , i.e.  is self-adjoin.

From the analysis above, the operator

, (4)

with energy units and  denoting adjoint, is deduced straightforwardly. It should be noted that , so that the geometric features of interference described by  are independent from the number of single photons moving in the MD volume. For  individual experimental realizations of single photon interference, this operator determines the non-locality at D

, (5)

as well as the energy of the recorded photons at each detector pixel

. (6)

Equations (5) and (6) provide the exhaustive description of any individual experimental realization in the Preparation-and-Measurement configured interferometers, as discussed in the next section. It should be emphasized that Eqs. (5) and (6) do not describe a many-particle system, no matter that  grows arbitrarily. Actually, they describe the formation of single photon interference patterns as the accumulative outcome of  individual experimental realizations without connections between them. So, each individual realization is strictly an independent only-one-particle system.

Therefore,  in Eq. (4) is the fundamental mathematical concept for the complete quantum description of single photon interference experiments. We call it the *quantum interference operator*.

1. **STATES OF SPACE**

The binary segments of a single photon interference experiment are characterized by the sequence , . In the absence of photons, Eq. (4) gives

, (7)

which is quite different from the standard paraxial approximated result (**Walls & Milburn,** 1995). The significant novelty evidenced by Eq. (7) is that the non-paraxial geometric features of interference remain in vacuum, i.e. in the absence of photons in the setup. More precisely, they seem to be independent from the presence of photons, thus remaining unchanged along the binary sequence of the experiment. So, ordinary space seems to be a system with geometric states of vacuum energy , described by the density operator  (**Castañeda et al,** 2023). The contrast of this conception of ordinary space and the Newtonian description of space in the standard interference formalisms invites the community to discuss the role of ordinary space in interference.

In addition, the coefficient  in Eq. (7) behaves as a filter placed at M, that selects and weights the geometric states of space in vacuum, thus characterizing each specific interferometer. Such a filter, defined in Eq. (2), is realized by the interference device, usually a mask, with the effective non-local transmission , under the prepared non-locality . This role of the setup in the absence of photons invites to revisit the phenomenological fundamentals of quantum mechanics (**Bohr,** 1935), by considering that the interpretation above does not result from heuristic assumptions but from direct phenomenological analysis of the mathematical model.

In order to determine the geometric states of space in the quantum interference operator in vacuum, it is useful to introduce the dimensionless function  in the integrand of Eq. (7), with  the Dirac delta. It gives

. (8)

where  is the *density operator of excited states of space* (**Castañeda et al,** 2023),

 (9)

provided by the term , is the *density operator of ground states of space* labelled at the points  of M, and

, (10)

given by the term , is the density operator of non-local geometric excitation modes, called the *geometric potential operator* (**Castañeda et al,** 2023). The density operators  and  are independent to each other.

In Eq. (9),  denotes the transmittance of M without polarizers (**Born & Wolf,** 1993), while  represents the effective transmittance with polarizers. Therefore, the coefficient  determines the quantum probability of finding a single photon emerging from  (See Supplementary Information for details). In turn, each non-local mode  of  in Eq. (10) provides the same geometrical excitation at a time to the both ground states of space labelled at the pair of points  of M. The excitation is activated by the non-locality  that links these points. Thus, each individual ground state of space should be geometrically excited by . So,  involves the spectrum of spatial modulations that excite the ground states of space , thus producing the excited geometric states . Such spectrum is filtered (selected and weighted) by the non-locality at M for any single photon interferometer, and it is not activated if  for any . In this case, none of the ground states of space are excited, so that the geometric states of space reduce to the ground states, i.e. .

**4. PREPARATION AND MEASUREMENT SCHEME**

**4.1 Space states for non-locality preparation**

Figure 1 depicts the conceptual configuration of single photon interference setups, called the P&M (Preparation-and-Measurement) scheme. Equation (8) gives the interference operator in vacuum for the MD-stage and, after expressing it in reduced coordinates of the SM-stage, it also gives the interference operator in vacuum for this stage. However, the geometric potential is not activated in SM-stage, because the individual experimental realizations of single photon interference experiments are independent of each other. Therefore, only ground states of space are established in SM-stage, so that,

. (11)

**Figure 1.** Conceptual sketch of single photon interference setup in the P&M (Preparation-and-Measurement) scheme. The expressions are explained in the text.

The projection of the interference operator in Eq. (11) on pairs of points of M gives the prepared non-locality at M , with

. (12)

It is remarkable that non-locality at S is not required to prepare non-locality at M. Moreover, only one ground state of space is able to prepare the non-locality  at M, as illustrated in Fig. 2. This exact numerical simulation points out that Eq. (12) describes cones in ordinary space with vertices at specific points  of S, bases on the region of pairs of points  of M, centered at a given  and Lorentzian cross-sections at any distance from S. The cone angular aperture is ~80°.

**Figure 2.** Non-locality Lorentzian cone for a single ground state of space, prepared in SM-stage of Fig. 1. (a) Cross-section at  () and (b) axial section for  Well vertex is at  on S. Non-locality support centered at  on M is described by (a) and the vertical profile in (b). Horizontal and vertical axes are the cartesian components of  in (a), and  and mutually parallel components of  on left side and  on right side in (b). Axes units are  and scale is in dimensionless arbitrary units.

The prepared non-locality  is corresponding to the cross-section at M of the overlapped ground states in Eq. (11). The area of the cross-section centered at , in which the prepared non-locality takes on non-negligible values, determines its support (**Castañeda et al,** 2023) and specifies the non-locality links between pairs of points  symmetrically distributed with respect to . Such links are negligible or nullify for pairs of points with separation vectors longer than the non-locality support diameter.

It should be emphasized that the ground states establish Lorentzian cones in ordinary space for non-locality preparation, which are compatible with the local nature of the photon emissions by the source. Indeed, the factor  in Eq. (12) determines the quantum probability for a single photon to be emitted at the cone vertex . Nevertheless, the preparation of such quantum probability does not require the presence of photons in the setup.

The set of ground states of space with vertices at the emitting points of an extended photon source is non-separable. Indeed, the complex valued function in Eq. (12) is non-factorable and, because of its harmonic factor, Eq. (11) implies that each ground state is spatially modulated by the remaining ones. As a consequence, non-locality spatially structured Lorentzian cones result, as illustrated in Fig. 3, for spacing of vertex array longer than  in (a)-(c), and shorter than  in (d)-(f). Because of the non-separability of ground states for non-locality preparation, the set associated with all emitting points should be included in integral of Eq. (11), no matter that the emission of the single photon in any individual experimental realization is a local event occurred at a specific source point.

**Figure 3.** Spatially structured non-locality cones established by an array of 3x3 ground states of space in SM-stage of the setup in Fig. 1. Horizontal and vertical array spacing are  in (a)-(c) and  in (d)-(f) (). Cross-sections at  on left column and  on central column, and axial sections for  on right column. Cone vertices are at the 3x3 array of emitting points at S and their basis are centered at  on M. Prepared non-locality supports are described by graphs on central column and vertical profiles on right column. Horizontal and vertical axes of cross-sections are the components of the separation vectors . Axial-section axes are  (horizontal) and mutually parallel components of  on the left vertical edge and  on the right vertical edge. The axes units are  and scale is in dimensionless arbitrary units.

Now, the projection of  on individual points of M gives the real valued, positive definite and separable functions

, (13)

that determine a Lorentzian cone in the SM-stage, with angular aperture of ~70° and vertex at the emission point , so that  as , as illustrated in Fig. 4. It is worth noting that the complex valued function in Eq. (12) cannot determine an observable, so that the prepared non-locality at M in Eq. (11) is not measurable by a square modulus detector. In contrast, Eq. (13) characterizes such observable by determining the quantum probability of finding the emitted single photon at any point  of M in each individual experimental realization, as

. (14)

**Figure 4.** Lorentzian well for a single ground state of space in SM-stage of Fig. 1. (a) Cross-section at  () and (b) axial section for . Well vertex is at  on S. Vertical profile in (b) shows the Lorentzian profile of the cross-section. Horizontal and vertical axes are the cartesian components of  in (a), and  and mutually parallel components of  on left side and  on right side in (b). Axes units are  and scale is in dimensionless arbitrary units.

Nevertheless, the vertex position of this Lorentzian cone is restricted by the geometric uncertainty, in the sense that it can be any point within an area of diameter  around each point  of S (**Castañeda et al**, 2020; 2023).

The numerical simulation of the exact (non-paraxial) Eq. (14) in Fig. 4 illustrates some important phenomenological implications, i.e. (i) it is compatible with a corpuscular characterization of the single photon; (ii) its Lorentzian profile distributes the quantum probability of emission in a conical volume, maintaining the largest probability along the cone axis; therefore, the cross-section in Fig. 4 (a) describes the expectation of single photon measurements at M; (iii) once the SM-stage is configured, all the functions  are established with the same geometry, given by . These features suggest that  determines a Lorentzian well for single photon propagation, from each emitting point of S to any point of M. Such Lorentzian well confines the photon preferably around the axis. This description is supported by a rigorous exact (non-paraxial) deduction, and the confinement precises the unrestricted spatial behavior attributed to the photons by the paraxial approximated formalism, thus increasing the description accuracy.

**4.2 Space states for interference measurement**

The quantum interference operator in vacuum, Eq. (8), gives the quantum probability for single photon arrivals to the detector pixel at any point  of D as follows

, (15)

where the ground states of space establish the Lorentzian wells

 (16)

in the MD-stage, as illustrated in Fig. 5, and the geometric potential provides the excitation

. (17)

In Eq. (17), Re denotes the real part and the following features are considered: (i) , (ii) the hermitian symmetry of integrand in Eq. (10) for permutation , and (iii) the addition of the integrand terms for the two degrees of freedom in orientation of the separation vector, i.e. . Therefore, the geometric potential  is real-valued and takes on positive and negative values, as illustrated in Fig. 6 (a)-(c).

**Figure 5.** Lorentzian well provided by an array of 3x3 base states of space in MD-stage. (a) Array of vertex points at M, with horizontal and vertical spacing of  (). (b) Cross-section at .(c) Axial sections for . Horizontal and vertical axes: (a), (b) cartesian components of , (c) and mutually parallel cartesian components of  at the left edge and  at the right edge. Axes units in  and scale is in dimensionless arbitrary units.

Equation (15) reduces to  if  for , and Eq. (16) points out that the Lorentzian wells cannot spatially modulate to each other by overlapping in , as illustrated in Fig. 5. Therefore, the geometric potential is necessary and sufficient to excite the ground states, thus producing the spatially structured Lorentzian wells  required for interference, as those illustrated in Fig. 6. It implies  for .

**Figure 6.** Cross-sections (left and central columns) and axial sections (right column) of the geometric potential on top row and the spatially structured Lorentzian wells on bottom row of example in Fig. 5, under maximum prepared non-locality at M.

It should be emphasized that both the vertex position of the geometric states of space and the excitation provided by the geometric potential are restricted by the geometric uncertainty (**Castañeda et al**, 2020; 2023). Indeed, the vertex position can be any point within an area of diameter  around each considered point  of M, and the geometric potential cannot excite the space states whose vertex separation is no longer than . Consequently, such area is associated to a unique ground state of space with vertex at any point within the area. It has been shown that this geometric uncertainty cannot be removed or reduced.

Because of the geometric uncertainty, the configuration of the mask placed at M and the prepared non-locality on this plane, a discrete and finite set of geometric states of space is established in the MD-stage of the setup. This set is filtered (selected and weighted) by the non-locality . More precisely, its local component for , , determines the quantum probability that filters the set of ground states, while its non-local component for , , filters the set of geometric potential modes that excite these ground states. Such excitations consists only in configuring specific distributions of zones of non-null quantum probability in the volume of the Lorentzian wells. In this way, spatially structured Lorentzian wells are stablished in MD-stage, where the concentration of quantum probability characterizes the confinement zones. However, the spatially structured Lorentzian well of each individual geometric state of space, , takes on non-positive values at the points  in which  and , as illustrated in Fig. 7. Such points configure forbidden regions for confinement, because confinement is characterized by the concentration of quantum probability that configures the observable to be measured by a square modulus detector (**Castañeda,** 2022). Nevertheless, the condition  for  must be fulfilled in order to ensure the achievement of Eq. (15). This means that:

1. The set of geometric excited states of space is non-separable because the space state overlapping is required to fulfil Eq. (15).
2. The forbidden zones are excited by the geometric potential, whose modes are non-factorable quantities. Indeed, the geometric potential operator in Eq. (17) takes the non-factorable form

**Figure 7.** Cross-sections (left and central columns) and axial sections (right column) of some individual spatially structured Lorentzian wells of example in Fig. 6, bottom row. White dots of cross-section on left column denote the vertex of the corresponding well.

. (18)

Consequently, the density operator of geometric states of space  becomes non-factorable for high non-locality values .

1. Forbidden zones of each individual geometric state of space must coincide with confinement zones of the remaining space states, in such a way that the forbidden regions are removed by addition of the space states. As a consequence, the values of the confinement zones of each geometric state of space diminish because of the negative values of the coincident forbidden zones of the remaining space states. It can be clearly formalized without loss of generality by considering the two geometric states of space in a Young interferometer, whose vertices are placed at the mask pinholes in . Therefore, the inequality

 (19)

is fulfilled except over the forbidden zones of .

The features above suggest a new type of entanglement between the geometric states of space, that we call *spatial entanglement* (**Castañeda,** 2022), (**Castañeda et al,** 2023). Usually, the term entanglement denotes certain interactions at a distance between photons or matter particles (**Hessmo et al,** 2003), (**Jones & Wiseman,** 2011). In the proposed theory, this term denotes that pairs of geometric states of space with vertex separation longer than the geometric uncertainty limit can modify the confinement zones of each other, in the absence of photons. In this sense, geometric states of space under high-valued prepared non-locality become spatially entangled at their forbidden zones.

The individual geometric states of space can be numerically modified by considering their spatial entanglement, in such a way that  and . These modified space states should provide the quantum probabilities for single photon detection in the individual experimental realizations. However, their measurement is an open challenge for experimentalists, mainly because of the stringent restrictions established by quantum eraser experiments (**Scully & Zubairy,** 1997), (**Rueckne & Peidle,** 2013).

**Figure 8.** Cross-sections at  on the upper row and  on the second row () of the modified individual excited states of space by spatial entanglement in MD-stage, and (i), (j) the complete excited state, for single photon interference with 2x2 array of points at M, under high prepared non-locality. The points are placed on the vertices of a square of side length . Closed contours in graphs (a)-(h) denote the forbidden zones set to null by spatial entanglement. Horizontal and vertical axes: cartesian components of  in . Scale is in dimensionless arbitrary units.

Because each geometric potential mode excites only a specific pair of space states, the modification of a set of geometric states of space should be performed by pairs. For the monomodal Young interference, the modification is performed as follows:

*  for the confinement zones, where .
*  for the forbidden zones, where 
*  for the spatial entanglement zones, where  and .

**Figure 9.** Cross-sections at  of the complete excited state for single photon interference with the 2x2 array of points in Fig. 8, under gaussian prepared non-locality at M, with standard deviation (a)  and (b) .

Figure 8 shows, in (a)-(h), the cross-sections of the individual modified excited states of space, for an array of 2x2 points at M under high prepared non-locality. The closed contours denote the forbidden zones set to null by spatial entanglement modification. The cross-sections in (i), (j) result by overlapping the wells of the individual modified excited states of space. They determine the interference patterns to be recorded.

However, by suitably weakening the prepared non-locality, the forbidden regions are removed, and therefore the spatial entanglement between the excited states of space is removed too, although the excitation provided by the geometric potential modes is yet visible, as illustrated in Fig. 9. These results show that single photon interference without spatial entanglement is feasible, too.

**5. THEORETICAL DESCRIPTION OF THE INDIVIDUAL EXPERIMENTAL REALIZATION**

The theoretical term “individual experimental realization” denotes the interval for  of the binary sequence ,  of the basic experiment segment in single photon interference.

It is well-established that single photons can be created by local emissions, resulting from atomic transitions of matter that specify its frequency , and can be annihilated by local detection at a pixel of a square modulus detector (**Saleh & Teich**, 2019). Photon corpuscular nature is also well-established as a particle of quantum energy  (**Mandel & Wolf,** 1995). In P&M-configured setups for single photon interference (Fig. 1) a photon source and a square modulus detector are placed at S and D planes, respectively. The interference device, usually a mask, is placed at a third plane, M, placed between S and D. Local observables for photon emission at S and photon arrivals at M and D are determined by the quantum probabilities  in Eq. (11),  and  given by Eqs. (14) and Eq. (15), respectively. Therefore, the single photon of any individual experimental realization should be considered as a particle moving in the interferometer. The localizability of such particle in the setup is restricted by both the quantum and the geometric uncertainties. However, the determination of the specific photon path is irrelevant for both the phenomenological explanation of interference and the mathematical prediction of the experimental outcomes. In contrast, the following description should be the relevant characterization of an individual experimental realization in the framework of the proposed model:

1. The single photon, locally emitted by the source with a specific quantum probability enters the ground state of space with vertex at the emission point, and moves confined in the volume of the corresponding Lorentzian well until locally arriving at any point of the interference device in the well basis.
2. If the arriving point is opaque, then the photon is annihilated by absorption by the device. If the arriving point is transparent, then the single photon crosses the device with a specific quantum probability and enters the geometric state of space with vertex at the crossing point.
3. If the prepared non-locality at M links the crossed point with other transparent points of the device, then the space state is excited by the geometric potential, thus establishing a spatially structured Lorentzian well in the volume delimited by the interference device and the detector. The single photon moves confined in any of the confinement zones of this well until being locally measured by the detector.

The description above results from a direct phenomenological interpretation of the mathematical model, for which further premises or hypothesis to those set out above about the corpuscular nature of the photon and its behavior in the setup, have been not advanced. Therefore, the local events of source emission, mask crossing and detector recording, and the photon confinement in the spatially structured Lorentzian well of any geometric state of space in the setup, characterizes the proposed theory as a corpuscular framework. By including single matter particle interference in ordinary space that can be explained in the same way by this theory, the proposed corpuscular framework should motivate the community to revisit the phenomenology of the wave nature of interference.

The canonical equation for the quantum interference operator is expressed as

, (20)

with  for SM-stage,  for MD-stage and , that implies . Therefore, the canonical quantum interference operator for any individual experimental realization is

. (21)

Equation (21) points out that one photon of quantum energy  propagates confined in the geometrical states of space of vacuum energy , established in the setup, and its arrival to a plane of reduced coordinates  is canonically described by

, (22)

with  for SM-stage and  for MD-stage. Therefore, the single photon emitted at  of S moves confined in the Lorentzian well with vertex at this point and arrives to any point  of M in accordance to , with . The arriving point is placed within the non-locality support given by , with . Now, let us consider that (i) the arriving point  is transparent and, (ii) there are transparent points , so that the pairs  belong to non-locality supports, centered at . So, the single photon that arrives at  enters the individual geometric state of space , excited by , i.e. the geometric potential composed by the subset of modes, which are activated by the prepared non-locality for pairs of points . The single photon cannot be confined in the forbidden zones of , and the probability to be confined in a spatially entangled zone, given by , is lower than the corresponding value given by . Consequently, the single photon moves in MD-stage effectively confined in the modified geometric state of space , so that its detection by any pixel of the detector at D is described by  where  represents the quantum probability of finding the single photon at the point  of D. So, the modified quantum interference operator by spatial entanglement,  describes the effective single photon confinement in the individual experimental realization, represented by the modified geometric state of space . So, the canonical quantum interference operator can describe exhaustively any individual experimental realization of single photon interference in ordinary space, and points out that they are not pure random events because of the deterministic Lorentzian wells in SM-stage and spatially structured Lorentzian wells in MD-stage established by . The statistical appearance of single photon detections in the complete interference experiment is due to the statistics of source emissions and mask crossings, the quantum and geometric uncertainties that randomize the confinement in the established zones in each individual experimental realization, and finally, the quantum sensitivity of the detector that determines its detection rate. However, this statistical appearance is compatible with the deterministic geometries of the space states established in the experimental setup.

**6. CONCLUSIONS**

The rigorously deduced quantum interference operator describes non-paraxial single photon interference as resulting from the photon confinement in geometric states of space, filtered (i.e. selected and weighted) by the setup. This exact second-order mathematical tool confers a physical meaning to geometry in interference, as relativity did for gravity. It implies an epistemological departure from the standard interference formalism, based on the paraxially approximated first-order procedure of wave superposition, that motivates the discussion by the community.

More precisely, in this framework ordinary space is considered as a system with geometric states provided by vacuum, i.e. in the absence of photons and with the vacuum energy. Ground states of space can be geometrically excited (i.e. spatially modulated) by geometric potential modes. Such modes are activated by prepared non-locality functions, also provided by vacuum. This conception of ordinary space completely differs from the Newtonian passive scenario of the standard interference formalism. Indeed, the geometric states of space determine interference, in such a way that the patterns recorded as experimental outcomes are effectively space states maps, performed by the single photons that move along their confinement zones.

The corpuscular framework of the proposed theory is remarkable. It also explains single matter particle non-paraxial interference in the same way, thus inviting the community to revisit the wave nature attributed to interference. In addition, the description does not resort to wave-particle duality and associated hypotheses to describe interference (i. e. particle delocalization, self-interference and wave collapse, for instance). It only requires the notion of confinement as phenomenological principle to explain interference in a generalized context (i.e. including classical light and matter particles, too) (**Castañeda et al**, 2023). Furthermore, the quantum interference operator introduces new interference features, not evidenced by the standard formalism, such as the geometric uncertainty and the spatial entanglement.

It should be emphasized that the phenomenology of the interference operator is referred to ordinary space, which is the environment where interference experimentally occurs, instead of only to calculate the probability distributions of experimental outcomes in Hilbert space, as established in quantum mechanics. From this point of view, our model could be considered as a realistic theory, which is also compatible with classical light interference, by considering a significant large number of photons emitted at a time. Because of their bosonic nature, photons can occupy the geometric states of space at a time, thus filling their confinement zones. For , the interference operator gives the well-known result  for the light irradiance (**Saleh & Teich,** 2019). In addition, the angular factors of the effective transmission  lead to the achievement of the Malus’ and Fresnel-Arago’s classical laws of polarization (**Born & Wolf,** 1993).

Because of the attributes above, the phenomenology provided by the quantum interference operator seems to be more effective than the standard formalism for explaining interference in ordinary space. From this perspective, the proposed theory opens a pertinent discussion on the foundations of interference, the review of its philosophical implications and the performing of new experiments to examine the validity of the alternative phenomenology.

**Author contributions:** The authors contributed equally to the discussion of the subject and the paper preparation.

Conflict of interest:The authors declare no conflicts of interest.

Data availability: No data were generated or analyzed in the presented research.

**Funding Statement:** This work was carried out under research program *Semillero 2241 - Ciencia de la Luz* of the Universidad Nacional de Colombia.

**Ethical compliance:** This requirement is not applicable in this study.

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