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Fresnel Equations Derived Using a Non-Local Hidden-Variable Particle Theory

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Abstract

Problem: The Fresnel equations describe the proportions of reflected and transmitted light from a surface, and are conventionally derived from wave theory continuum mechanics. Particle-based derivations of the Fresnel equations appear not to exist. **Approach:** The objective of this work was to derive the basic optical laws from first principles from a particle basis. The particle model used was the Cordus theory, a type of non-local hidden-variable (NLHV) theory that predicts specific substructures to the photon and other particles. **Findings:** The theory explains the origin of the orthogonal electrostatic and magnetic fields, and re-derives the refraction and reflection laws including Snell's law and critical angle, and the Fresnel equations for s and p-polarisation. These formulations are identical to those produced by electromagnetic wave theory. **Contribution:** The work provides a comprehensive derivation and physical explanation of the basic optical laws, which appears not to have previously been shown from a particle basis. **Implications:** The primary implications are for suggesting routes for the theoretical advancement of fundamental physics. The Cordus NLHV particle theory explains optical phenomena, yet it also explains other physical phenomena including some otherwise only accessible through quantum mechanics (such as the electron spin g-factor) and general relativity (including the Lorentz and relativistic Doppler). It also provides solutions for phenomena of unknown causation, such as asymmetrical baryogenesis, unification of the interactions, and reasons for nuclide stability/instability. Consequently, the implication is that NLHV theories have the potential to represent a deeper physics that may underpin and unify quantum mechanics, general relativity, and wave theory.

Keywords

Wave-Particle Duality, Optical Law, Fresnel Equation, Non-Local Hidden-Variable

1. Introduction

This paper presents a particle derivation of the Fresnel equations for a single photon, using the Cordus theory [1]. No special difficulty exists in explaining optical phenomena of reflection and refraction from an electromagnetic (EM) wave basis, which assumes an underlying continuum mechanics. In particular, the Fresnel equations may be derived for s and p polarised light [2] using continuity of the electric and magnetic fields (Gauss' Law). These equations give the proportions of light that will be reflected and transmitted for a given angle of incidence, for the two orthogonal polarisation components. Extant derivations are based on continuous rays of light [3]. However particle-based derivations of the Fresnel equations are non-trivial and appear not to exist.

The Fresnel equations were originally derived for macroscopic optical structures [2] but are also applicable for smaller optical structures such as material microstructure grain [4], stacks of multiple thin layers of optical material including beamsplitters [5], and two-dimensional heterostructure materials [6]. Consequently, they appear to apply down to scales at which quantum mechanics (QM) usually applies. However, there is no derivation of the Fresnel equations available from quantum mechanics, nor apparently from any other particle basis. This is part of the wider incongruence of wave-particle duality. The traveling wave approach to soliton propagation has been applied to optical phenomena e.g. bifurcation in optical fibres [7] and the interaction of wave elements [8] including rogue waves [9]. This approach provides a mathematical model for nonlinear behaviours [10], typically using a polynomial complete discriminant method [11] [12] [13] and has primarily been applied to wave propagation effects, optical as well as water, but also other effects such as nerve signal propagation [14]. While mathematically powerful and able to model complex wave phenomena, this approach does not appear to have resulted in an explicit derivation for the Fresnel equations. Furthermore the nature of such modelling is that it does not provide an ontological explanation for physical phenomena—as in the current objective—but rather is premised on and builds onto existing physics. Hence there is no overlap between the objectives and methods of the current paper and the literature on travelling waves.

There are several impediments to producing a particle derivation of the Fresnel equations. The particle perspective of quantum mechanics requires that fundamental particles be zero-dimensional (0-D) points [15]. While polarisation may be defined for such entities, it is an intrinsic mathematical parameter, and has no physicality within QM. Fresnel's key insight was the identification that light waves had an elastic component, the magnetic field, transverse to the direction of propagation. This concept is unavailable to QM, since there is no reason for a single 0-D photon to have a transverse component. Models that include elements of string theory may be able to recover elements of the Fresnel equation by assuming particles are semi-infinite rods [16]. Other that these exceptions there appears not to have been a serious theoretical reconceptualization or alternative derivation of the Fresnel equations.

2. Methods

2.1. Objectives

The objective of this work was to derive the Fresnel equations and other key optical formulae from a particle perspective. More specifically the theoretical starting point was the Cordus theory, a type of non-local hidden-variable (NLHV) theory.

Unlike quantum theory that is premised on the assumption that particles can only be 0-D points, the NLHV theories propose that particles have substructure. The non-local hidden-variable theories have become obscure and unorthodox, but this was not always the case. The difficulty with the traditional NLHV approach is that it has been theoretically unproductive, despite early enthusiasm [17]. The best known NLHV theory is the de Broglie-Bohm theory [18], but even that does not address the optical question.

The current paper uses a more recent NLHV theory, the Cordus theory [1]. Appropriate parts of this are briefly summarised below where necessary, and for a fuller description see [19] [20]. The Cordus theory is not limited to a narrow area of relevance. Instead, it has successfully explained multiple phenomena in physics and cosmology (see Discussion for references).

2.2. Approach

The Cordus theory was taken as the basic particle model from which to start [1] [21] [22] [23] [24]. This defines a specific substructure for the particle, primarily characterised by the particle having two ends some distance apart: these are termed the *reactive ends.* They are proposed to energise in turn, and be joined by a *fibril* which is unreactive with matter. During energisation the reactive ends emit *discrete fields* in a flux tube. These discrete forces have a sinusoidal strength function and (for massy particles) are energised in sequence in the three Cartesian axes [19] [20].

The Cordus theory is not a development of quantum electrodynamics or quantum field theory (QFT). Rather, the field structures proposed by the Cordus theory arise from logical consideration of preceeding work within its own body of knowledge. Even so, there are elements of similarity between quantum field theory and Cordus theory: both incorporate harmonic oscillators that are always oscillating irrespective of their energy state—as does conventional wave theory; both propose that the field structure corresponds to identity of type of particle—though the Cordus theory goes further in showing how this results in structure within the atomic nucleus; both describe a mechanism for action at a distance. There are also differences in the proposed causal mechanisms, the interpretations of decay processes and the weak interaction, the treatment of gravitation (not integrated into QFT but is Cordus theory), and in the approach to theory development (QFD takes a computational approach while the Cordus theory takes a conceptual design approach).

The explanation for how an electron moves [20] is of special significance, as it proposes that the electron has an orbital excursion motion at each of its two reactive ends. When exposed to an external field, this warps into a spiral type motion. This motion has periods of dwell and hence the overall picture is of an intermittent motion, which is referred to as "gait locomotion". This orbital motion has a causal relationship with the particle's emissions. In the present paper this concept is adapted and applied to the photon.

The magnetism part of the Cordus theory [25] is also useful. Along with the motion part of the theory, it explains magnetism as signalling that the charge-emitting reactive end has deviated from a straight locus. This magnetism arises as a transverse component to the electrostatic field emissions [20] for moving charged particle.

The argument presented in this manuscript does not depend on the case for a deeper unification of gravitation and the strong force, as described elsewhere [20] [25] [26]. Nonetheless a key conceptual part of the present paper is that of the proposed emission field structures, so it is necessary that these field structures be described. All that is claimed is that conceptually these emission structures are able to explain both the Fresnel equations and the full range of interactions.

The results have three parts. The first develops a conceptual model of the photon substructures, more detailed than given in [1] [21] [22] [23] [24]. This also identifies a origin for the orthogonal electrical and magnetic oscillation of the photon, which is crucial for the subsequent developments. The second part sets out a theoretical basis for refraction and reflection from a particle basis. The third part derives the Fresnel equations.

3. Proposed Substructures of the Electron and Photon Particles

The NLHV theories expect that particles have substructure, and the Cordus theory predicts a specific geometric and functional morphology of this substructure. The electron and photon substructures are summarised below.

3.1. Electron Emission Structures

The electron emission structures have been previously described in [19] [20] [25] [27] and are summarised as follows. The discrete force emissions have a sinusoidal function with potential energy $U = \sin^2(\theta/2)$ where $\theta = \omega t$ and ω is the angular velocity related to the energisation frequency. New discrete forces continue to be created, released, and sent down the flux tube at each frequency cycle. The discrete force emissions do not subtract energy from the particle. The emission may be resolved into a triphasic emission across the three principal axes [a, r, t], offset 120˚ in phase angle. See **Figure 1** for a graphical representation.

The particle aligns its [a] axis in the axial direction of linear motion (if any),

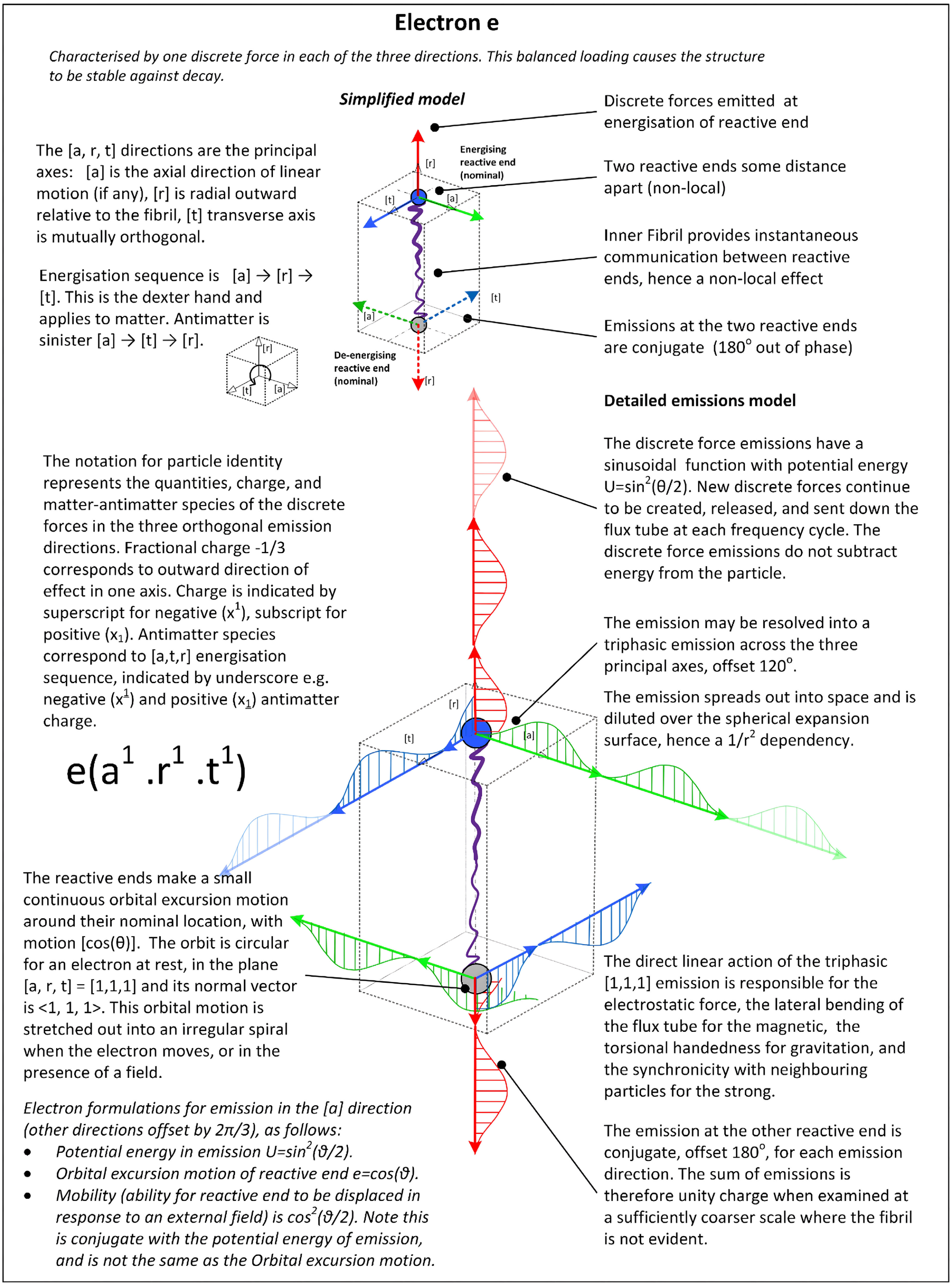

Figure 1. The representation of the electron's internal and external structures. It is proposed that the particle has three orthogonal discrete forces, energised in turn at each reactive end.

[r] being the radial outward direction determined by the fibril that connects the two reactive ends, and the [t] transverse axis being orthogonal to the other two. The nature of this orthogonality—of which only two hands are available, *i.e.* the available energisation sequences are limited to [a, r, t] and [a, t, r], is proposed as the matter-antimatter species differentiation [26] [28].

The emission spreads out into space and is diluted over the spherical expansion surface, hence a $1/r^2$ dependency for the field forces. The direct linear action of the emission is responsible for the electrostatic force, the lateral bending of the flux tube for the magnetic, the torsional handedness for gravitation [19], and the phase synchronicity [29] with neighbouring particles provides the strong force. Hence unification of forces is achieved [25]. The emission at the opposite reactive end is conjugate, offset 180˚, for each emission direction. The sum of emissions is therefore unity charge when examined at a sufficiently coarse scale where the fibril span may be neglected.

The reactive ends make a small continuous orbital motion around their nominal location, with motion [$\cos(\theta)$] conjugate to emission in the respective axis $U = \sin^2(\theta/2)$ [19]. The orbit is circular for an electron at rest and its normal vector is [a, r, t] = [1, 1, 1], which is also the particle identity. This orbital motion is stretched out into an irregular spiral when the electron moves, or in the presence of a field, with mobility (ability to be displaced by external discrete forces) of the reactive end as $\cos^2(\theta/2)$ conjugate with its emissions [20].

Relativistic considerations and derivation of the Lorentz from a particle perspective

A key concept in the Cordus theory is that of the flux tube. This concept is needed in the optical cases under examination, so a brief introduction is provided by way of explaining the relativistic Lorentz [30].

Consider a moving massy particle that emits a flux tube (discrete force) in the [r] direction as it passes point O, see **Figure 2**.

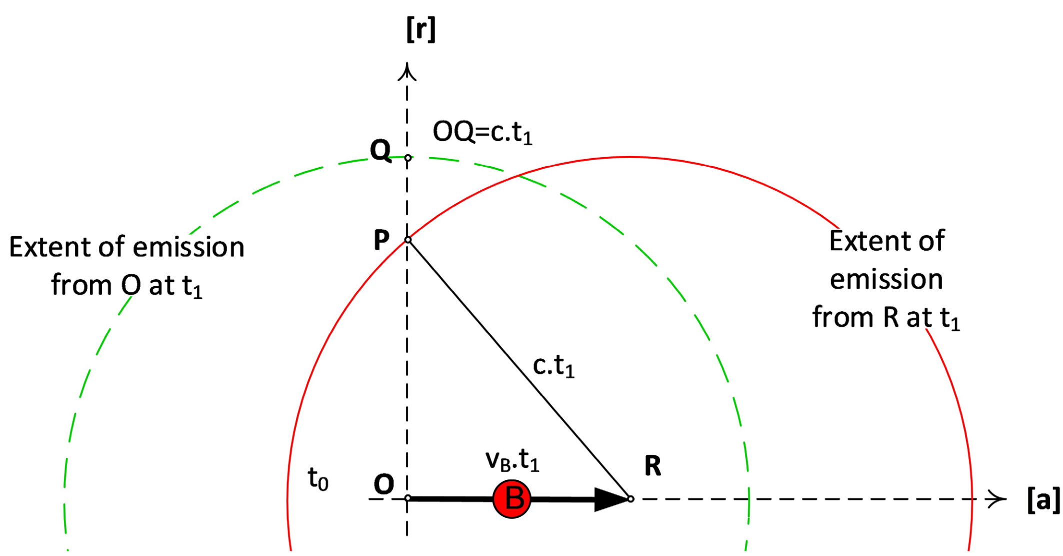

Figure 2. Geometric construction for Lorentz derivation, adapted from [30].

This $[r]$ emission moves out radially at the speed of light c and after a time interval t_1 the emission reaches point Q at distance $\overline{\mathrm{OQ}} = ct_1$. In that same interval the particle moves with velocity v in the axially direction and reaches point R at a distance of $\overline{\mathrm{OR}} = vt_1$. From point R the emissions nominally only reach point P on $\overline{\mathrm{OQ}}$, however the continuity of the flux tube requires it be stretched (hence red shifted) to reach Q. The relative stretch is:

$$\frac{\overline{\mathrm{OQ}}}{\overline{\mathrm{OP}}} = \frac{ct_1}{ct_1\sqrt{1-\left(\frac{v_B}{c}\right)^2}} = \frac{1}{\sqrt{1-\frac{v_B^2}{c^2}}} = \gamma \tag{1}$$

This is the formulation for the Lorentz factor γ, thus demonstrating the feasibility of deriving the Lorentz from a particle basis. The flux tube principle is also relevant to optical phenomena as will be shown.

For the electron the discrete forces are emitted and released to propagate outwards indefinitely, with new discrete forces continuing to be created and sent down the flux tube at each frequency cycle. Also, the electron has an emission in all three axes, each of which carriers a −1/3 fractional charge, hence the unit negative charge of that particle.

3.2. Photon Substructures

In contrast the characteristics of the photon are that it does not release its discrete forces, but rather emits them into the fabric and then absorbs them again [1]. The fabric refers to the surrounding sea of discrete forces from all the other matter particles in the accessible universe [30]. Hence the emissions of the photon do not extend out into space like that of the electron, but is instead highly localised. The photon stores its energy in the field it creates in the fabric. This is an evanescent field—it does not propagate. The photon shuttles this energy to express it alternately at its two reactive ends. This is shown diagrammatically in **Figure 3**.

Related to this is the way in which the two reactive ends are coordinated. For the photon, both reactive ends are simultaneously active, and they both process the same emission. One reactive end pushes the emission into the fabric, and the other withdraws it at the other side of the fibril span, hence the potential energy that is stored in the field oscillates from one to the other. The emission status of the two reactive ends is complementary—at any one moment in time the strength of emission is the same at both reactive ends, and in the same absolute direction. In contrast the electron emissions across the two reactive ends are conjugate—their potential energy sums to unity. The photon reactive ends behave as one, as though there is no physical distance between them. This is achieved by the superluminal connectivity of the fibril. This also means that the photon is non-local, which entanglement experiments show it to be [31].

The photon in the Cordus theory is believed to have only one emission, which is in the $[r]$ direction. This is inferred from other parts of the theory that describe the way the photon is emitted from matter [22] [24]. The lack of emissions in the

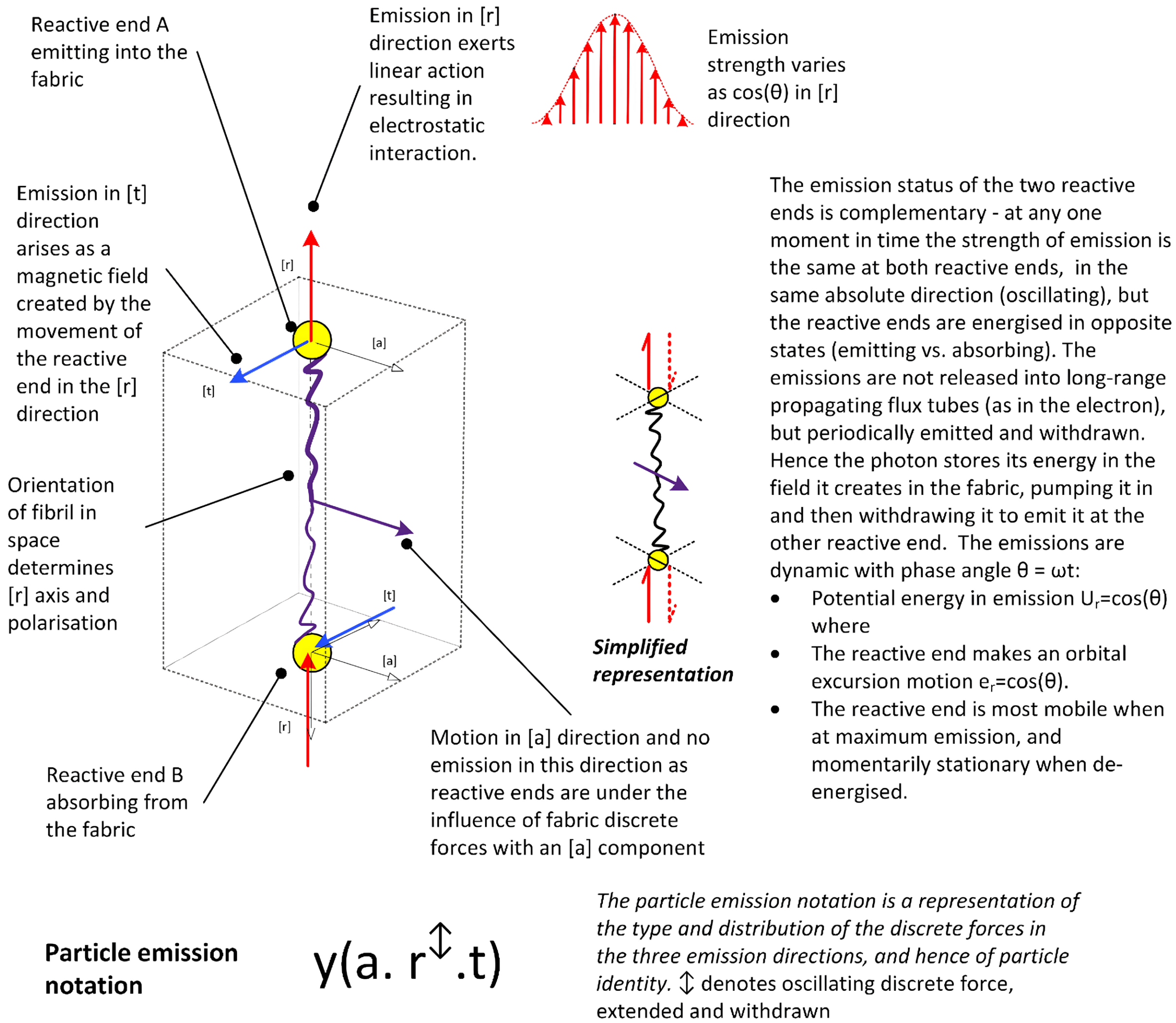

Figure 3. The photon's substructures and field emissions.

other directions [*a*] and [*t*] is held to be the reason why the photon lacks the stability to exist in stationary form. Rather it moves through the fabric, to compensate for the lack of emissions. The fabric is matter handed, in that it contains discrete force emissions from matter particles (like the electron described above). The handedness is expressed in the energisation sequence [*a*, *r*, *t*] of matter particles, and this is encoded as a torsional effect in the flux tubes comprising the fabric. Although the photon itself is not handed, nonetheless in its temporary adoption of discrete forces from the fabric to assist its motion, it is exposed to the [*a*, *r*, *t*] energisation sequence. Consequently, like the electron, we propose that it arranges its [*a*] axis in the direction of motion, [*r*] axis perpendicular to the motion (and corresponding to fibril orientation and hence also to polarisation), and [*t*] axis transverse to them both [20].

As with the electron, the photon reactive ends are is believed to make an orbital excursion motion (*e*) around their nominal location. For the primary energisation in the [*r*] direction, this is a periodic motion function $E_r = \cos(\theta)$, with normal vector <0, 1, 0>. As the photon also moves forward in the [a] direction, this results in the locus of the reactive end having a sinusoidal function in 3D space. There is no emission in the [*a*] direction as that is the direction of motion. The motion is assumed to be approximately continuous.

In the transverse [*t*] direction a magnetic field emission results. The *physical* reasons for why the magnetic field should be orthogonal to the electric field are not self-obvious, and electromagnetic wave theory does not offer a fully satisfactory explanation, and quantum theory none at all. The Cordus theory is useful here as it offers a deeper explanation for magnetism [25], whereby the movement of the electrostatic field generator—in this case the reactive end with its [*r*] emission—causes a bend in the flux tube. Recall that in this theory the tension of the flux tube corresponds to the electrostatic interaction, the curvature (or bending) thereof to magnetic force, and the torsion within the flux tube (from the energisation phase sequence) to the gravitational interaction. The purpose of the magnetic field is to encourage neighbouring co-moving charged particles to move in the same signed direction as the basal emitter. Hence the photon's emission in the [*r*] direction, and the accompanying orbital movement of the reactive, creates a magnetic field. The direction of emission is perpendicular to the plane of the curvature of the flux tube, hence orthogonal to the [*r*] and [*a*] directions in which that curvature occurs.

It is known that the electrostatic and magnetic fields are in-phase, *i.e.* cis-phasic rather than trans-phasic for light waves. In the present theory this implies that the photon has a different relationship between the orbital motion of the reactive end, and the emission in the [*r*] direction. Specifically, for the photon it is proposed that the emission in the [*r*] direction is strongest when the reactive end is fully mobile, and the magnetic field in the [*t*] direction arises in response to movement and emission in the [*a*, *r*] plane, and is *in phase* with the [*r*] electrostatic emission. Note this is different to the electron model.

4. Basic Optical Effects

4.1. Interaction between Photons and the Electrons in the Bulk

It is necessary to develop a conceptual framework for how such a photon interacts with the electrons in the bulk media, *i.e.* when it is propagating in a straight line. During transmission through the first medium with refractive index n_1 the photon engages with the medium. The medium comprises other particles (atoms, electrons) and the fabric Ø emissions from distant particles. Several cases deserve particular elaboration. The following are conceptual propositions for the mechanisms.

Photon in vacuum

In the case where the photon is travelling through a vacuum, there may not be electrons in the bulk of the medium, but there are fields from all the other matter particles in the accessible universe, *i.e.* a fabric density Ø of discrete fields exists [30], and the photon engages with this. Hence the emission from the reactive end is required to be affected by the fabric density ∅. It has been proposed that it is the density of this fabric that determines the speed of light in vacuum [32]. Since the spatial distribution of matter is uneven across the universe and between time epochs in the evolution of the universe, this theory predicts a variable speed of light in-vacuo.

Photon motion in a dielectric

In the case where the photon is travelling through say glass, there are electrons in the bulk of the medium, and the photon interacts with these in passing. This interaction is proposed as the cause of the reduced speed of light in such cases. The delay is proposed to occur because the photon needs to temporarily recruit suitably aligned fields from the fabric, and a denser fabric (higher refractive index) presents more such opportunities, and thus a smaller axial displacement of the reactive end at each energisation cycle.

The refractive index is a measure of the capacity of the medium to engage with the photon, and the greater the refractive index the more electrons the photon's E and B fields will perturb. These interactions are loss-less, but even so these electrons will move somewhat, which produces electromotive forces that affect the motion of the photon reactive end, *i.e.* slow it down for $n_2 > n_1$. These evanescent E and B fields may be felt by remote particles. For example coupled waveguides appear to work by coupling the evanescent fields across a physical gap [33]. The two tracks are able to periodically exchange power by synchronisation of phase. These devices show a dependency on photon frequency [34].

4.2. Polarisation

The convention in electromagnetic wave theory is that the polarisation direction is determined by the direction of the electric field (rather than the magnetic) relative to a reference plane, in this case the plane of incidence. For p-polarisation the [r] emission is parallel to the incident plane, and for s-polarisation it is perpendicular. Both wave theory and quantum mechanics are premised on the photon lacking internal structure or identifiable spatially orientated features, and consequently neither theory provides an ontological explanation for why the electric and magnetic fields take specific spatial orientations.

The current theory offers a physical interpretation. Here the polarisation of the photon is the physical orientation of the fibril [27], in particular the orientation of the electric field in the [r] emission direction. It is proposed that polarisation arises from two causes. First, the emission of a photon (e.g. from an electron) naturally results in an orientation being imposed on the photon fibril, because the electron itself is also a linear structure [22]. Second, during transmission the crystalline structure of the medium selectively attenuates inconsistent photons.

We define the *fibril plane* as the [a, r] plane of the photon, that is the plane made by the fibril span and the direction of motion. Then the p and s polarisation states are attributed to orientation of this plane relative to the plane of observation or incidence, see **Figure 4**.

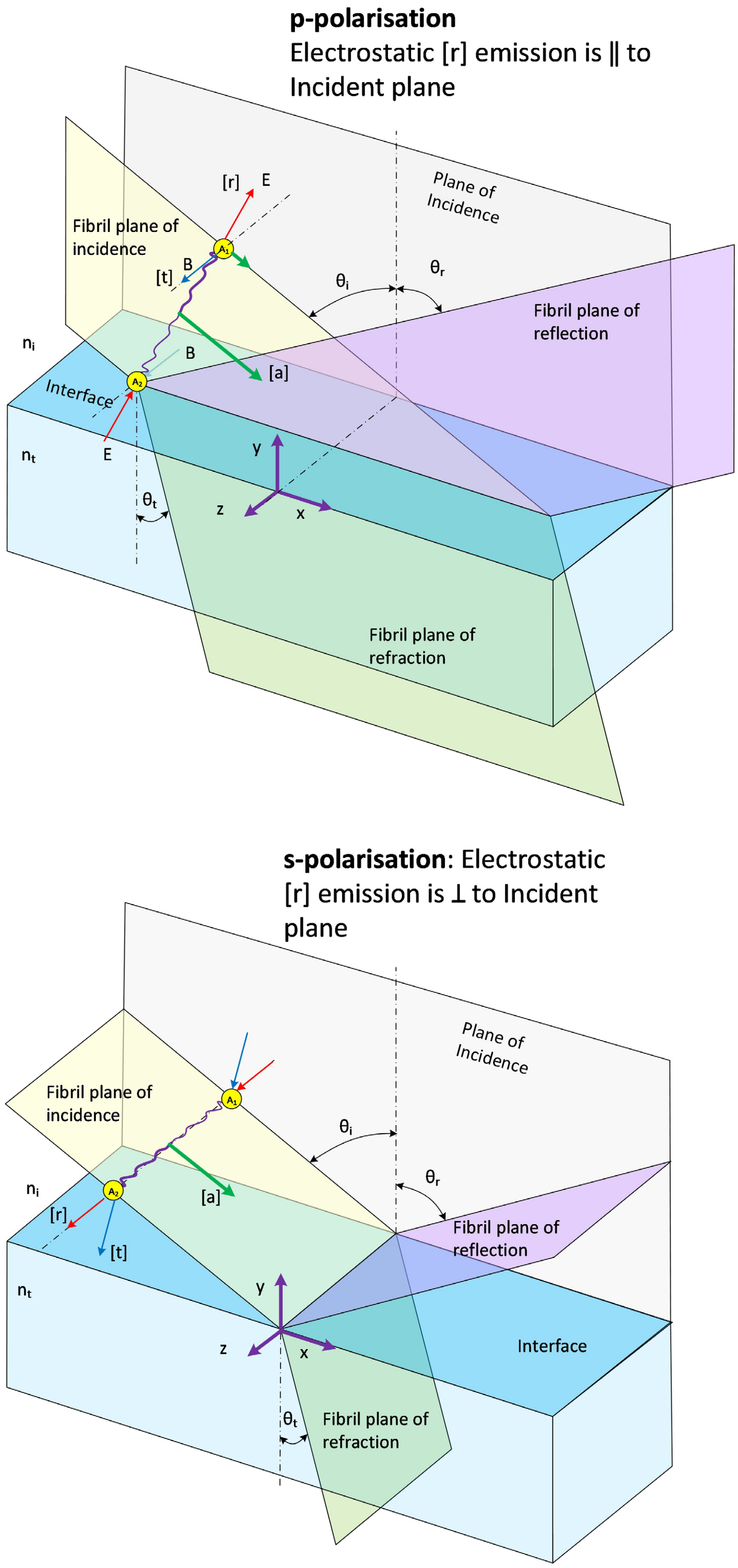

Figure 4. Physical interpretation of the two polarisation states in the Cordus theory. (a) p-polarisation, (b) s-polarisation.

Further, it will be shown in the Fresnel derivation that this also gives a natural explanation for the signs of the field continuity equations across the interface, thereby clearing up another vague area in the conventional derivation.

The above explanation for the photon internal structures includes two key features that are important in the derivation of the Fresnel equations. The first is the concept of the photon having a span (between the two reactive ends), hence polarisation is given a physical meaning (as discussed above). Secondly, a reason is given for the existence of an electric field in the [*r*] direction (in the direction of the span and hence related to polarisation) and for a magnetic field orthogonal to both the electric field and the direction of motion. Note that the reason for the orthogonality of the magnetic field has also been explained. This is not to deny that electromagnetic wave theory also represents the electric and magnetic fields as orthogonal, but here a deeper reason is offered as to the cause of this relationship.

Circular polarisation

Circular polarisation in the Cordus theory corresponds to a roll motion of the fibril around the axis of motion [*a*]. For linear motion, the proposed mechanism is that the fibril stores shear in the relevant direction, which acts on the reactive ends to move them forward [20]. Assuming the same mechanism may act in the transverse [*t*] direction, and noting that the [*t*] directions are—by consideration of handedness—opposite at the two reactive ends, a roll motion arises around the [*a*] axis. This is proposed as the physical explanation for circular polarisation. As regards the generation of the polarisation, conceptually this arises from anisotropic crystal structure or molecular-level helicity (and related effect of circular dichroism) of the medium through which the light passes, or radiated by a crossed dipole antenna with a phase difference in energisation across the orthogonal antenna field components. These mechanisms act differently on the electrostatic [*r*] and magnetic [*t*] components of the Cordus particle. As in the case of the linear motion of the electron and photon, once this rotation is established it is lossless and does not require energy to sustain. This explanation is consistent with the conventional explanation from wave theory, and also with spin [27] in quantum theory (and related spin angular momentum of the photon).

4.3. Refraction

Multiple derivations of Snell's law exist. The Huygens–Fresnel principle may be used to infer that the electric field of the wave interacts with electrons in the interface to radiate a series of new waves, which interfere to form the new but slower wave. Another derivation uses Fermat's principle of least time applied to a ray traversing the two media (with their different speeds

$$v = c/n = f\lambda \text{),} \tag{2}$$

assuming fixed start and end positions of the ray. Another uses the principle of wavenumber symmetry across the interface (the number of wavelengths per unit distance is

$$k = \omega/c = 2\pi/\lambda\ ),\tag{3}$$

with the wavelength changing but the frequency remaining constant. Early Cordus theory also provided a derivation, based on wavenumbers [1], but was limited to p-polarised photons. We now present a more general derivation for a single photon.

Derivation of Snell's law for s-polarisation

With respect to **Figure 5**, consider a photon with Cordus structure in the s-polarisation state as it approaches a surface.

The engagement sequence is shown in **Figure 6**. The electric emission $E[r]$ is perpendicular to the xy plane of incidence, and the magnetic field B is in the $[t]$ emission direction, hence in the xy plane of incidence (in the z direction). The field strength varies sinusoidally, but at any one instant is the same at both reactive ends A and B, though opposite in direction, this being a characteristic of the photon in the Cordus theory.

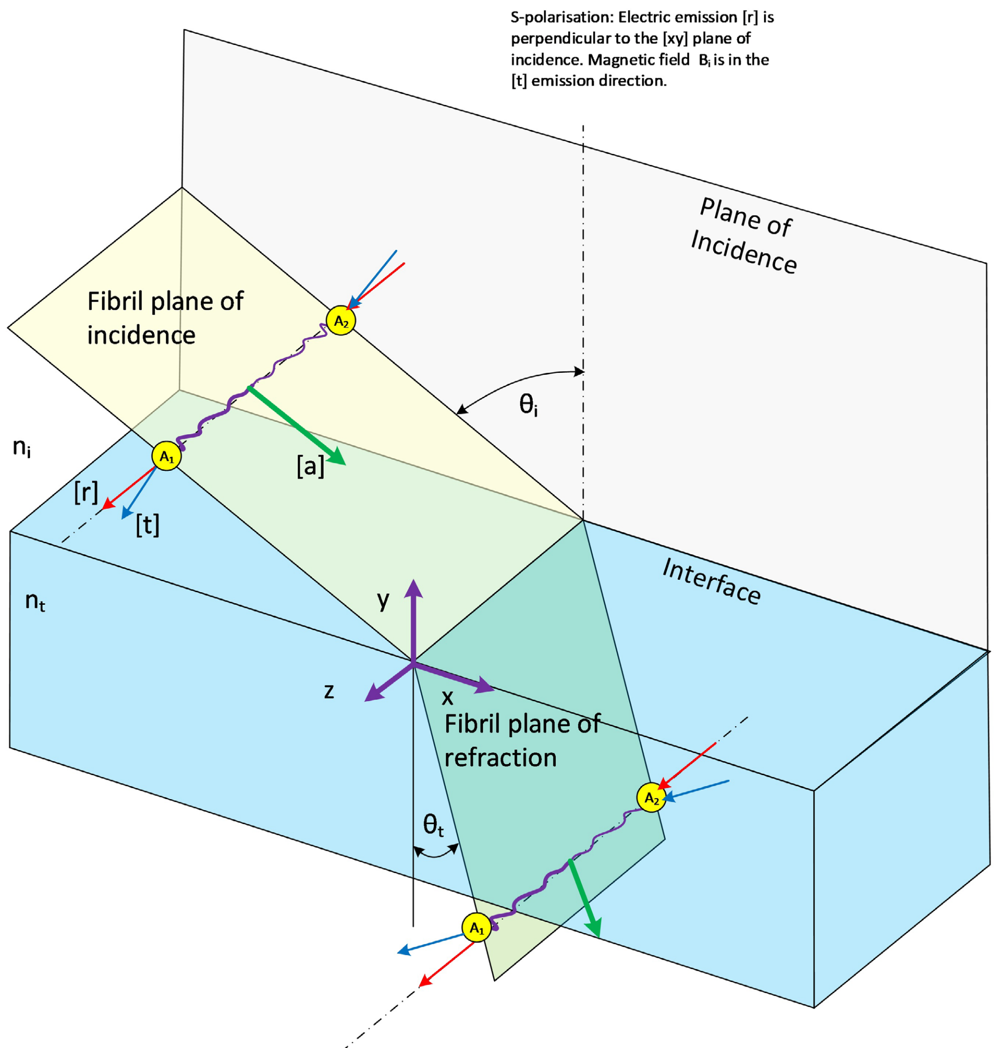

Figure 5. Arrangement for refraction with s-polarisation. Red arrow indicates electric field in $[r]$ direction, blue magnetic in $[t]$ direction.

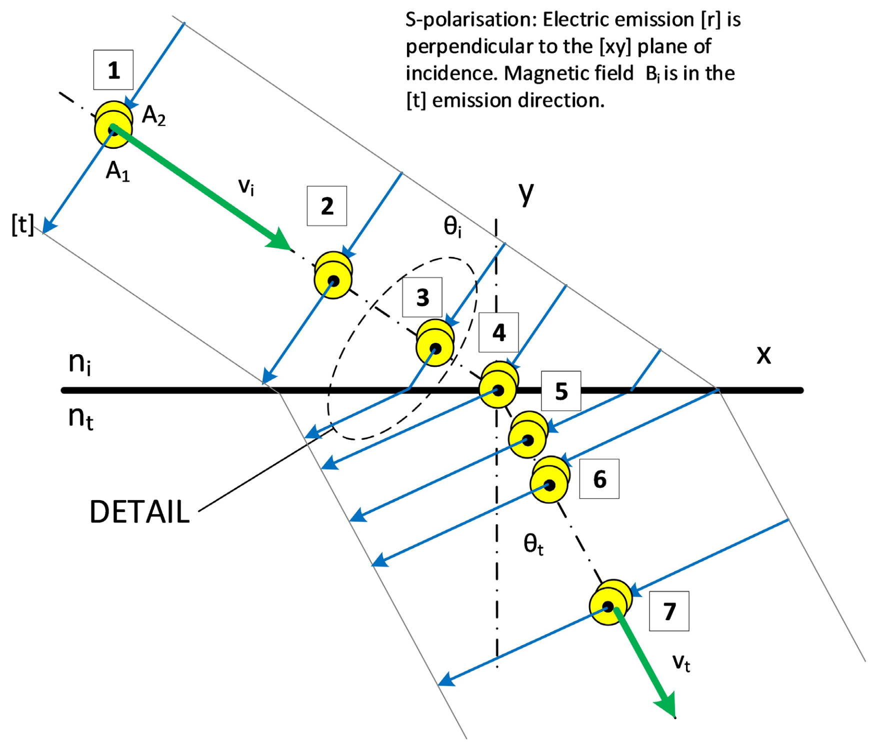

Figure 6. Stages in the transition of a photon with reactive ends A_1 and A_2 in s-polarisation moving with velocity v_i as it crosses an interface in the [xz] plane. Blue arrows (thin) indicate magnetic field amplitude, green arrows (thick) indicate velocity. Some details have been omitted at points [2 - 5] for clarity. The electric field is perpendicular to the view.

The particle derivation of Snell's law is as follows. As per the Lorentz derivation (above and [30]) the B field is dragged forward by the incident photon moving at velocity v_i in medium with refractive index n_i, see Figure 6. The figure is drawn with a constant magnetic field, whereas in practice this would be sinusoidal, however this is immaterial to the derivation. There comes a point [2] in the photon locus where the B field first encounters the second medium n_t. The photon itself is still in n_i and experiences no change of velocity as yet. However the forward motion of that part of the field in the second medium changes to

$$v_t = v_i n_i / n_t \,, \tag{4}$$

i.e. slower in the illustrated case for transition to a denser medium, e.g. air-to-glass. As the photon progresses to point [3], more of its B field protrudes into medium n_t and this component advances with velocity v_t, *i.e.* slower. Consequently the B field is bent backwards. The "marching soldier" analogy is valid here. The orientation of the distal portion of the field is orthogonal to v_t, whereas the proximal portion becomes orthogonal to v_i. This process continues through points [4] [5] [6] until eventually all the emissions are wholly in medium n_t.

Consider location [3] in Figure 7. The reactive end A_1 is at position Q_1 at distance $v_i dt$ away from the interface, with dt being a small time interval. There is a corresponding point P_1 on the B flux tube at the interface.

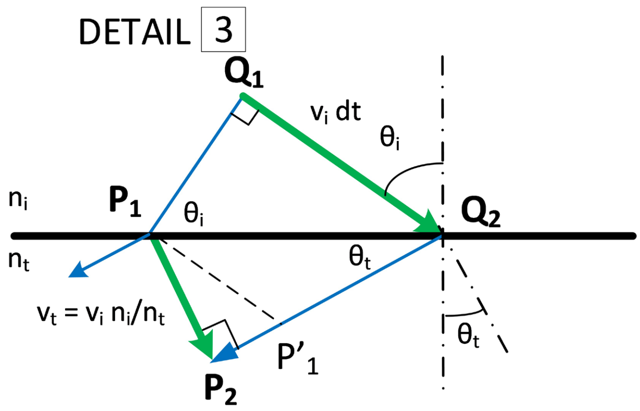

Figure 7. Detail of photon location [3], for s-polarisation.

After time dt the reactive end—and hence the origin of the flux tube—moves $v_i dt$ to Q_2. In the same time interval point P_1 on the B flux tube moves $v_t dt$ to P_2 in the direction of θ_t. (It does not move to P'$_1$ in the direction of θ_i). By geometric considerations:

$$v_i dt = \overline{P_1 Q_2} \sin \theta_i \tag{5}$$

and

$$v_t dt = \overline{P_1 Q_2} \sin \theta_t \tag{6}$$

Rearranging:

$$\overline{P_1 Q_2} = \frac{v_i dt}{\sin \theta_i} = \frac{v_t dt}{\sin \theta_t} \tag{7}$$

Hence:

$$\frac{\sin \theta_i}{v_i} = \frac{\sin \theta_t}{v_t} \tag{8}$$

Since $v \propto \frac{1}{n}$ then

$$n_i \sin \theta_i = n_t \sin \theta_t \quad \text{which is Snell's law.} \tag{9}$$

This derives Snell's law for a single photon using the Cordus theory. The derivation has a basis in physical realism (the change in velocity with refractive index is well-established), and is mathematically straightforward (simple geometric considerations are used and few steps are required).

Underpinning the derivation is the assumption that the emitted flux tube (field) moves forward as a wavefront through the medium. In the above diagrams the magnetic field is denoted in blue arrows signifying the direction of emission in the [t] direction of the photon. However the derivation made no specific identification, nor use, of the length of the arrows. We interpret the length as the magnetic flux density B. This is the field that arises in the medium in response to the magnetic field intensity H intrinsic to the reactive end, with $B = \mu H$ with μ being magnetic permeability and related to the refractive index as

$$n=\sqrt{(\epsilon\mu)/(\epsilon_o\mu_o)} \tag{10}$$

with electric permittivity ε and vacuum values ϵ_o and μ_o, as conventionally understood. If the derivation was done with p-polarisation then the electric field E would be under scrutiny and the electric permittivity would be relevant.

Derivation of Snell's law for p-polarisation

The derivation was provided for the more challenging case of s-polarisation, where the two reactive ends A_1 and A_2 are coincident in the view such that the magnetic field B is in the plane of incidence. The derivation also applies for the p-polarisation state where the electric field E is in the plane of incidence, and for an arbitrary polarisation where both E and B have components in that plane, see Figure 8.

Per Figure 8, the A_1 reactive end reaches the interface at position [4] and A_2 at [6], see detail in Figure 9. This arrangement is geometrically congruent with Figure 7, and the same logic applies to recover Snell's law again, this time for p-polarisation.

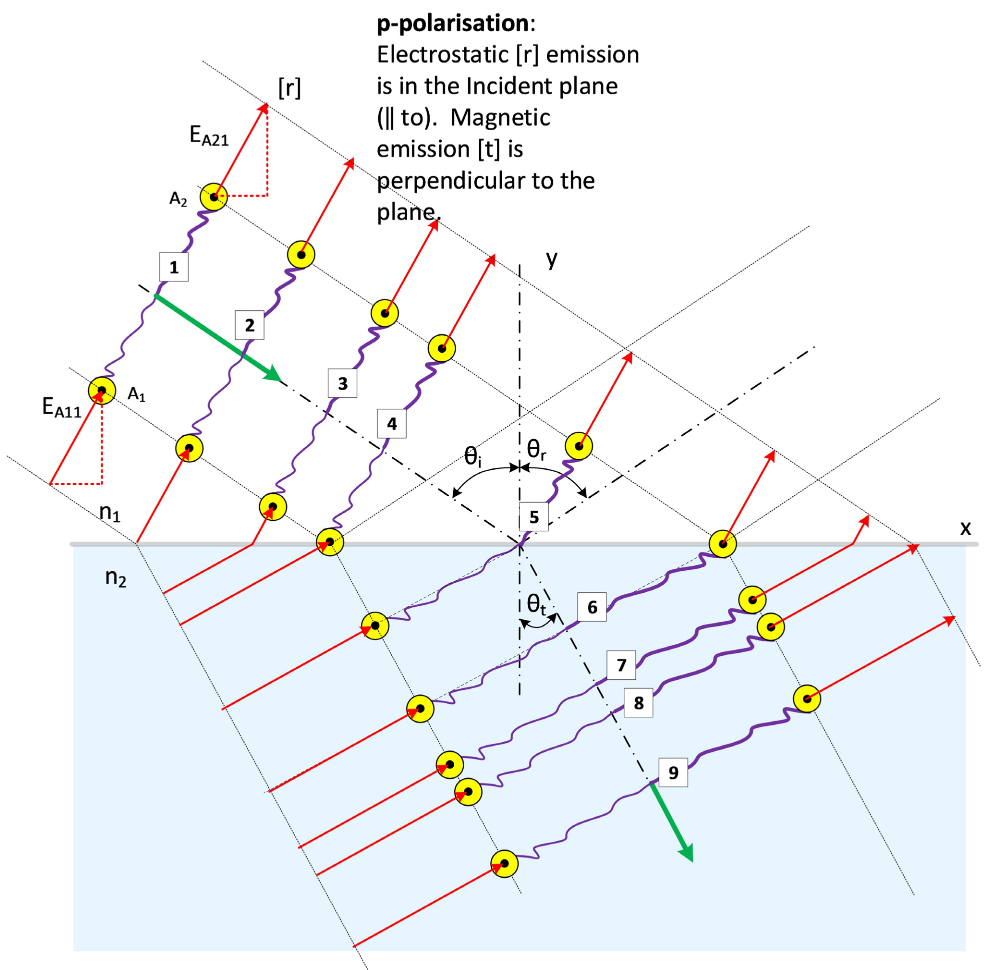

Figure 8. Refraction of a p-polarised photon. Reactive ends A_1 and A_2 are shown in a series of steps—not necessarily equal time steps—as they cross an interface in the [xz] plane. Red arrows indicate electric field, with magnetic field perpendicular to the view.

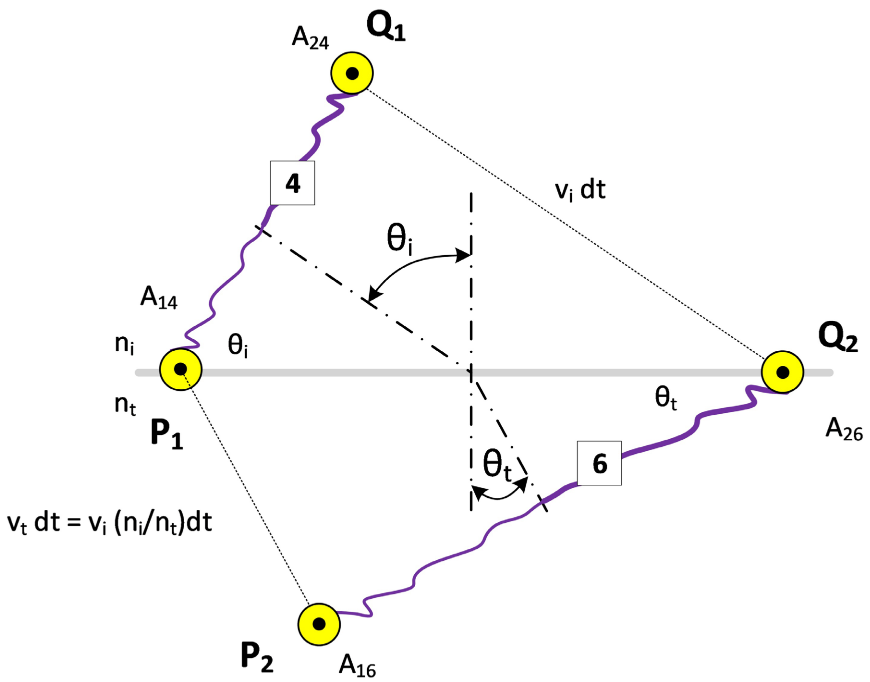

Figure 9. Detail of positions [3] and [6] of the photon locus, for p-polarisation.

These derivations have a number of limitations. One is the assumption of an unchanged magnetic and electric field through the transit, whereas it actually varies sinusoidally. This makes no difference to the derivation. A second is that the field (magnetic or electric) is shown orthogonal to the velocity vector, whereas it is believed to be dragged at a trailing angle per the Lorentz work above. This would change the details of the photon locus but is not expected to disqualify the derivation.

Derivation of critical angle

The critical angle is where all light is reflected off a medium of lower refractive index (total internal reflection). For the Cordus particle, this occurs—with reference to Figure 7—when P_2 is coincident with Q_2, which arises because of sufficiently greater propagation velocity v_t such that the distance $v_t dt = v_i\left(n_i/n_t\right)dt$. Hence the angle at which this occurs is:

$$\sin\theta_i = \frac{v_i dt}{v_t dt} = \frac{v_i}{v_i\left(n_i/n_t\right)} = \frac{n_t}{n_i} \tag{11}$$

which is the conventional form of the critical angle. This derivation was for s-polarisation, but applies equally to p-polarisation because Figure 7 and Figure 9 are congruent.

Discussion of Snell's law and equifinality of various derivations

This derivation does not invalidate the many other derivations of Snell's law. There appears to be an equifinality of outcome from multiple different starting points. These are briefly contrasted.

The method using the principle of no change in the transverse momentum reduces to a requirement of equal wavenumbers on each side of the interface.

However the explanation is weak for why only the transverse momentum is unchanged, and no physical mechanism is readily apparent for how a single photon would measure and conserve its wavelength. We interpret the wavelength requirement as being a proxy for *vdt* in the Cordus derivation.

Fermat's principle of least time requires start and end points, which might be relevant for a continuous wave but is an unworkable principle for a single photon. Why should the photon want to minimise time? Also, there is a navigation problem: the steering mechanism for the photon is not elaborated. The current Cordus derivation suggests that the navigation occurs by the field being bent at the change in medium, and time is a valid but only as a proxy variable.

The Huygens–Fresnel principle assumes that every point on the wavefront is the source of small new wavefronts, and that these interfere leaving only the new transmitted wavefront. It is a complicated theory because it calls for all the points in the medium to be radiating but only in the forward direction, and there are an infinite number of these in a continuous medium. We suggest that the principle works because the forward radiation is a proxy for emission propagation in a forward direction.

The equifinality of these various methods implies, from a philosophical perspective, that the externally measureable parameters of the photon are coupled, being coordinated by an internal causality, hence resulting in various valid ways to derive Snell's law of refraction. In turn this lends credence to the idea that the photon does have physical internal structure, and is not merely a 0-D point moving in space.

The derivation shown here using displacement (velocity and time) appears to be more fundamental than the others because it uses parameters with known or plausible physicality, is explicit about the mechanisms, does not require the photon to have navigational intelligence, and is valid for both particle and wave perspectives.

Secondary derivation of Snell's law

Using the above principle of equifinality we are able to offer a secondary derivation.

First, define the magnetic flux density as

$$B = Hn \tag{12}$$

and identify this as the characteristic time engagement of the emission, *i.e.* the extent to which the emission (intrinsic magnetic field intensity *H*) takes time to interact with the particles in the medium. A physical explanation is possible: This interaction involves storing and then retrieving the evanescent charge in the medium. A denser medium involves interacting with more electrons, and more small time delays caused by the necessity of the electrons to be in right parts of their own emission cycles. This delays the ability for the reactive end to emit and retrieve its charge from the external environment. This has the consequence of decreasing its ability make its own movement, *i.e.* its velocity slows (though its frequency remains unaltered). This property of the medium is measured by the refractive index. This could also be considered a temporal back-engagement of the medium on the photon.

Second, assume a requirement that the characteristic time engagement B_y in the direction perpendicular to the interface must be unchanged across the interface. This can be motivated by considering a photon on the interface, see point [4] in **Figure 10**. This photon has complementary emissions from its two reactive ends A_1 and A_2, but these are engaged with mediums n_1 and n_2 respectively. The fibril that connects these reactive ends ensures that they behave consistently (this is a requirement from the Cordus theory), and hence an equality is required in B_y. This still does not explain why there should be no equality in B_x—possibly this relates to electron mobility in the interface. Nonetheless, if we proceed on this assumption then Snell's law is immediately accessible by equating

$$B_{iy} = B_{ty} \tag{13}$$

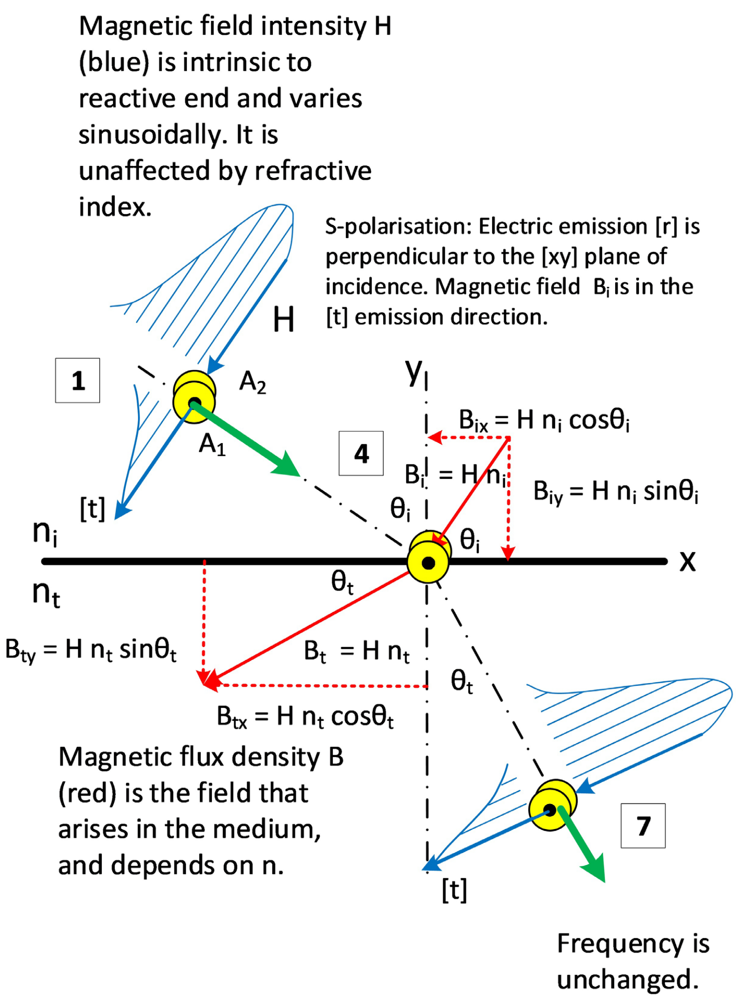

Figure 10. A secondary derivation of Snell's law. The photon moves from point [1] through to [4] as it crosses the interface in the [xz] plane. Identifying the magnetic flux density B as the characteristic time engagement of the flux tube, and requiring that the component perpendicular to the interface must be unchanged across the interface, leads directly to Snell's law.

hence

$$n_i \sin\theta_i = n_t \sin\theta_t \tag{14}$$

as H is constant across the interface.

This illustrates a potentially profound method: By exploring the many different ways in which Snell's law can be derived it could be possible to make further inferences about how the internal structures of the photon operate.

4.4. Reflection

Wave theory explains reflection as the interface absorbing and re-emitting waves. The multiple time-shifted emitted waves from the continuous input waves are held to interfere to produce the reflected wave. This is not a feasible way to explain reflection for a single particle, so a different approach is needed.

Reflection off a more dense medium

The reflection process itself may be understood as an application of Newton's law of reaction applied in the y direction as a consequence of elastic recoil via the E and B fields. However, there is still the ontological question of whether the single photon bounces off the surface, or is absorbed and re-emitted. Examination of the fields for the Cordus photon in s-polarisation undertaking a bounce manoeuvre, see **Figure 11**, identifies a problematic transition from position [6] to [7].

If instead we model a process where the photon is absorbed and re-emitted, the evolution of the field is more gradual, see **Figure 12**. The photon approaches

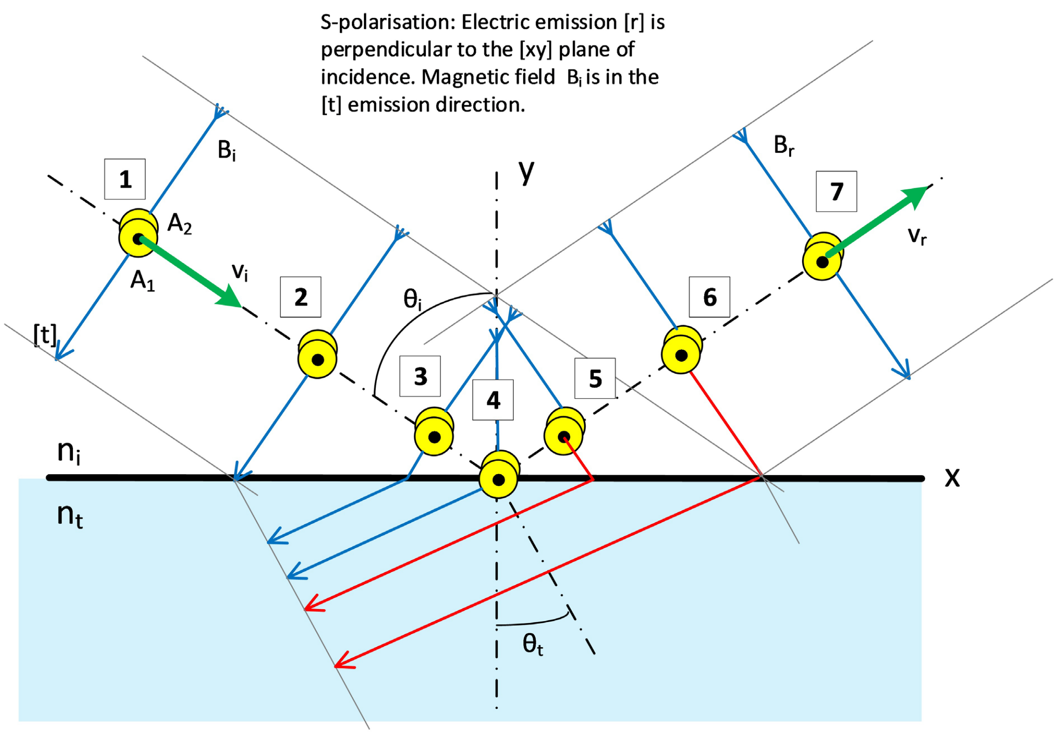

Figure 11. Reflection by the photon bouncing off a denser substrate is disfavoured in the Cordus theory as it would involve abrupt changes in the B fields at points [5] and [6].

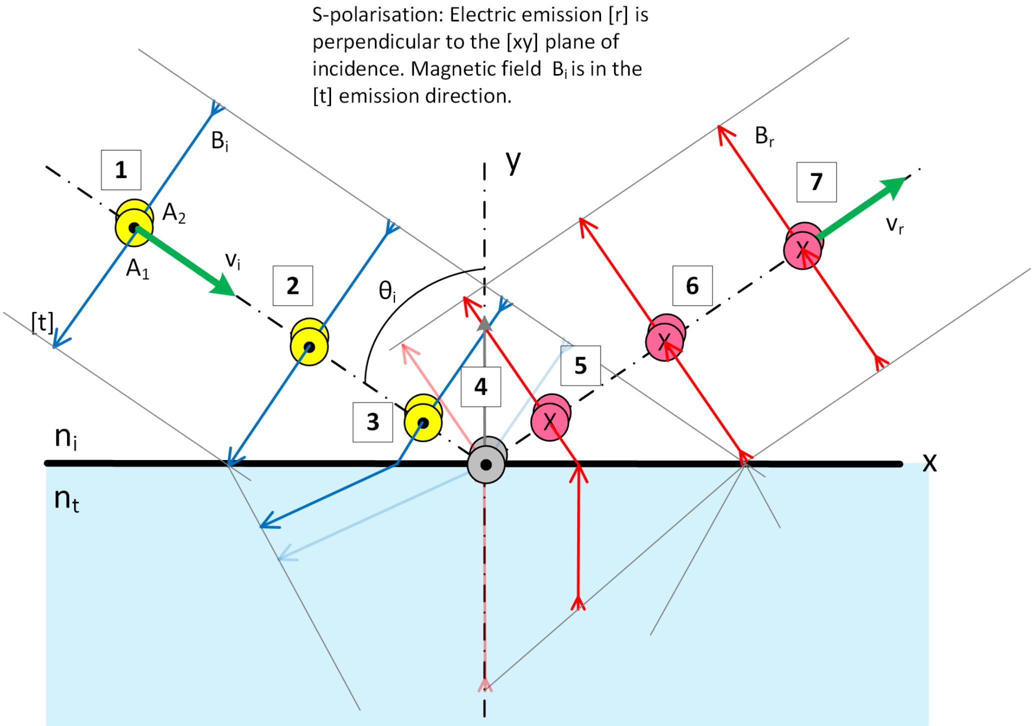

Figure 12. The process for approach of the incident photon [stages 1 - 3], its absorption [4], and its re-emission [5 - 7], showing the field evolution for s-polarisation for reflection off a more dense medium.

the interface and its fields interact with the surface [1 - 3]. The absorption avoids the discontinuity by resetting the fields. This is the more plausible of the two explanations and is therefore adopted.

At location [4] it is absorbed into an electron at each reactive end. Only one of the photon reactive ends needs to collapse—the fibril recalls the other. We propose that the photon fibril, as it collapses, also momentarily entangles the two electrons, *i.e.* synchronises their phases. The directional nature of the momentum imparted attempts to displace the electrons, but they experience a rigid-elastic constraint in the y direction, which requires re-emission of the photon. The photon momentum in the plane of the interface plane is accommodated by electron mobility. Elsewhere the Cordus theory offers detailed mechanisms whereby photons are emitted & absorbed [22] [24]. Once re-emission of the photon occurs at reflection the fields are re-established with directions appropriate for the reflected locus (locations 5 - 7).

It is conceivable that the directions of the field emissions change at reflection off a more dense medium (illustrated in **Figure 12**), though this is not a certain thing. It would be consistent with the known phenomena of a phase change at reflection off a denser medium[1]. In other wave situations, e.g. strings, the phase change occurs because atoms in a fixed end boundary produce elastic reaction

[1]Reflection off a more dense medium ($n_i < n_t$) causes a phase change of 180˚ in E and no change in B, with the exception that there is no change for p-polarised light at incident angles greater than Brewster's angle. However the Cordus theory does not explain all this complexity.

against the wavefront, causing the reflected wave to be inverted. Likewise a boundary condition where atoms are free to move in response to the wavefront (*i.e.* perpendicular to the velocity) causes reflection without phase inversion. Somewhat similar mechanisms could be at work in the photon case.

There are other intricacies about reflection for which the current theory also offers some partial explanations. Specifically, the Goos-Hänchen effect is a known small positive shift D_s in the [x] direction for the reflected beam [35]. Other studies show that the shift varies with polarisation: a smaller shift for s-polarised light reflecting, and a larger negative shift for p-polarised light, these studies being for reflection off a metal surface [36]. The conventional explanation requires a wave perspective, that the incident beam comprises multiple plane waves (with curved fronts) that interfere during the reflection [37], which does not admit a particle explanation. Nonetheless it is possible to give a particle description, albeit qualitative, using the above Cordus theory. We interpret this shift as arising because the electrons at position [4] (in **Figure 10** for s-polarisation) move slightly in the x direction between their absorption and re-emission of the photon, since these processes are not instantaneous but require a frequency cycle of the electron [22] [24]. In the case of p-polarisation the reactive ends strike the interface some distance apart in the x direction, and hence with a time separation, the receiving electrons have more time to move, and hence plausibly a larger shift.

Reflection off a less dense medium

Consideration of the *B* field propagation per **Figure 13** shows an orderly transition in the field structures. From point [2] through to [3] an increasing proportion

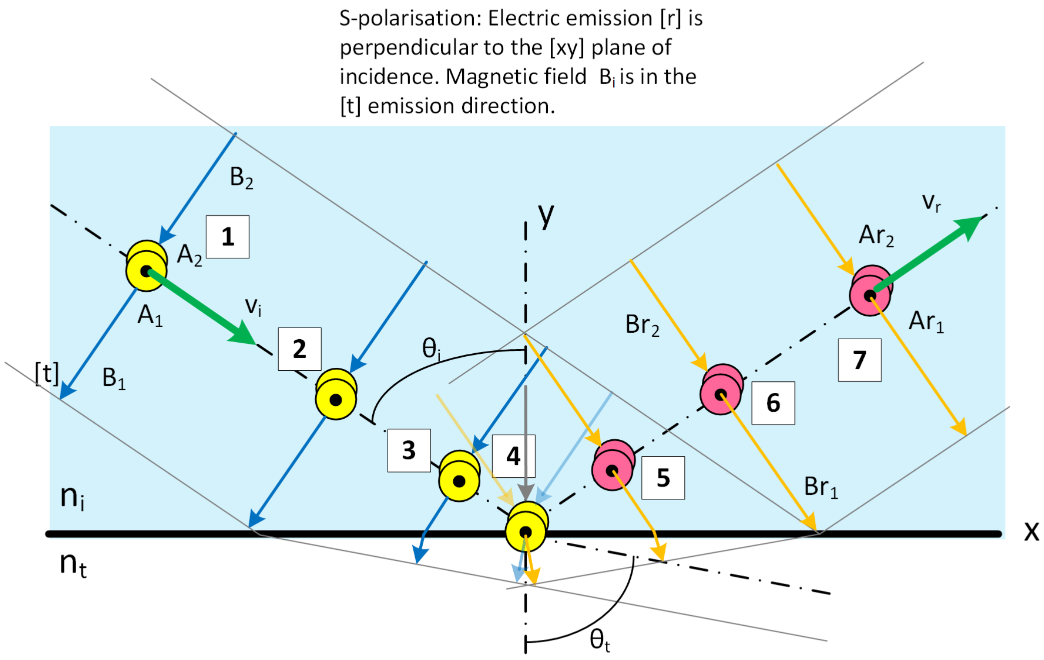

Figure 13. Reflection of a Cordus photon off a less dense medium, showing evolution of field structure for s-polarisation. The implication is that the photon is not absorbed.

of the field is in the second (less dense) medium, and this part of the B wavefront advances at faster speed v_t. At the crossover point between [4] and [5] there is a smooth transition for the $B_1 \rightarrow Br_1$ field, less so for $B_2 \rightarrow Br_2$. While the B wavefront is drawn as perpendicular to photon motion, it is believed to be trailing (per the Lorentz effect). In which case, the B transitions are even more manageable. Hence it is possible that the photon is not absorbed but simply bounced off the surface. This is consistent with the known effect of no phase change in electric field at reflection off a less dense medium.

5. Fresnel Equations

Basis for the Fresnel Equations

The Fresnel equations describe the electric field amplitudes—as opposed to the angles or the power—of the incident (i), reflected (r) and transmitted (refracted) (t) fields. In what follows these standard abbreviations are denoted as subscripts to distinguish them from the unrelated Cordus particle orientations.

The conventional Fresnel derivations assume a continuous light wave, and assume that the normal and tangential components are continuous across the interface for both the electric (E) and magnetic (B) fields. This is an assumption that there is no static charge density built up on the surface, nor a current density. This is physically natural from considerations of avoiding charge build up over time. The light wave is a flow of energy, and partitioning a single input into two separate reflected and transmitted flows is not conceptually problematic. There is a tacit assumption that the frequency of the light does not change, and the relative permeabilities of both materials are unity (μ, magnetising response to applied magnetic field, *i.e.* assumes non-magnetic materials) [4].

Physical basis for continuity for photon particles

For single photon particles there appears to be no existing derivation, and there are a number of difficulties before even starting. It is challenging to explain why continuity of E and B should also be the case for a single photon, and how the duality of reflected and transmitted outcomes arises from a single input particle. Conceptually there appear to be two ways to solve this.

One way to address the reflected-transmitted path duality is to assume that the input photon splits into two independent output photons, one for each of the reflection and transmission branches, and that these propagate simultaneously. Conceptually this might be achieved by the photon interacting with an electron in the substrate, which deflects part of the photon energy into the transmission path, and absorbs and re-emits the other part into the reflection path. The electron would be simultaneously processing all three fields, and hence under the influence of all three. Thus its positional constraints would require the sum of the fields above the surface to be equal to that immediately beneath it. This is indeed the premise underpinning the Fresnel equations. For a continuous light source, as applies in wave theory, this explanation is more sensible. However for a single particle it implies that the energy would be split, which implies a change in frequency that is not seen.

The second interpretation is that the input photon goes either into the reflected or the transmitted path, not both, depending on the state of some internal parameter at the time of reaching the interface. This parameter could be the energisation state, e.g. whether the reactive ends were energising or de-energising at the time. For this interpretation, any one input photon would take only one of the output paths. With a flux of photons in different phases of energisation, both paths would become substantiated over time. Previous Cordus theory developments propose that tunnelling in a beam splitter (or partial mirror) arises from the energisation state of the incoming photon [38]. There is possibly some empirical support for this interpretation, in that [39] showed that when a stream of unbunched photons (approximating a sequence of independent single photons) was directed on a 50:50 beam-splitter, the photons were detected at either the transmission or reflected output, not both ("a near absence of coincidence counts between the two detectors"). However the experiment was done with a beam-splitter, which is not a conventional interface between two media. In addition, a beam splitter has two input ports, one being unused, and quantum theory assumes that vacuum fluctuations enter therein [34] whereas this feature is absent from a conventional air-glass interface. What [39] achieved was half an interferometer, and hence their findings were not a definitive response to the question of how single photons behave at a conventional optical interface. Surprisingly, there appears to be no empirical study addressing this question.

The current work proceeds with the second interpretation, that single photons, when directed to an air-glass interface, are only reflected or refracted. This may be explained by assuming that the photon interacts dynamically with the electron over the full frequency cycle of the photon. The electron would be influenced by the incoming fields, while simultaneously storing them in preparation for both outcome paths, and then only committing to release the photon into one path when the all the attributes of the photon were known. Hence again the sum of the fields above the surface would be equal to that below. The photon also would be participating dynamically with its fibril coordinating the outcomes at both its reactive ends. The photon cannot collapse at one reactive end, and continue to exist at the other—the fibril communicates between them to arrive at a consistent outcome. Hence it is proposed that the single photon does take only one output path at a conventional optical surface, with the path selected by its frequency state relative to that of the electrons in the substrate.

Fresnel equation for p-polarisation

Physical interpretation

In the Cordus theory the p-polarisation case has a physical arrangement where the electrostatic [r] emission is parallel to the plane of incidence, and the magnetic [t] is perpendicular, as shown in **Figure 14**.

The derivation of the Fresnel equation follows. First, determine the field directions. The Cordus theory offers a physically natural way to do this. Applying

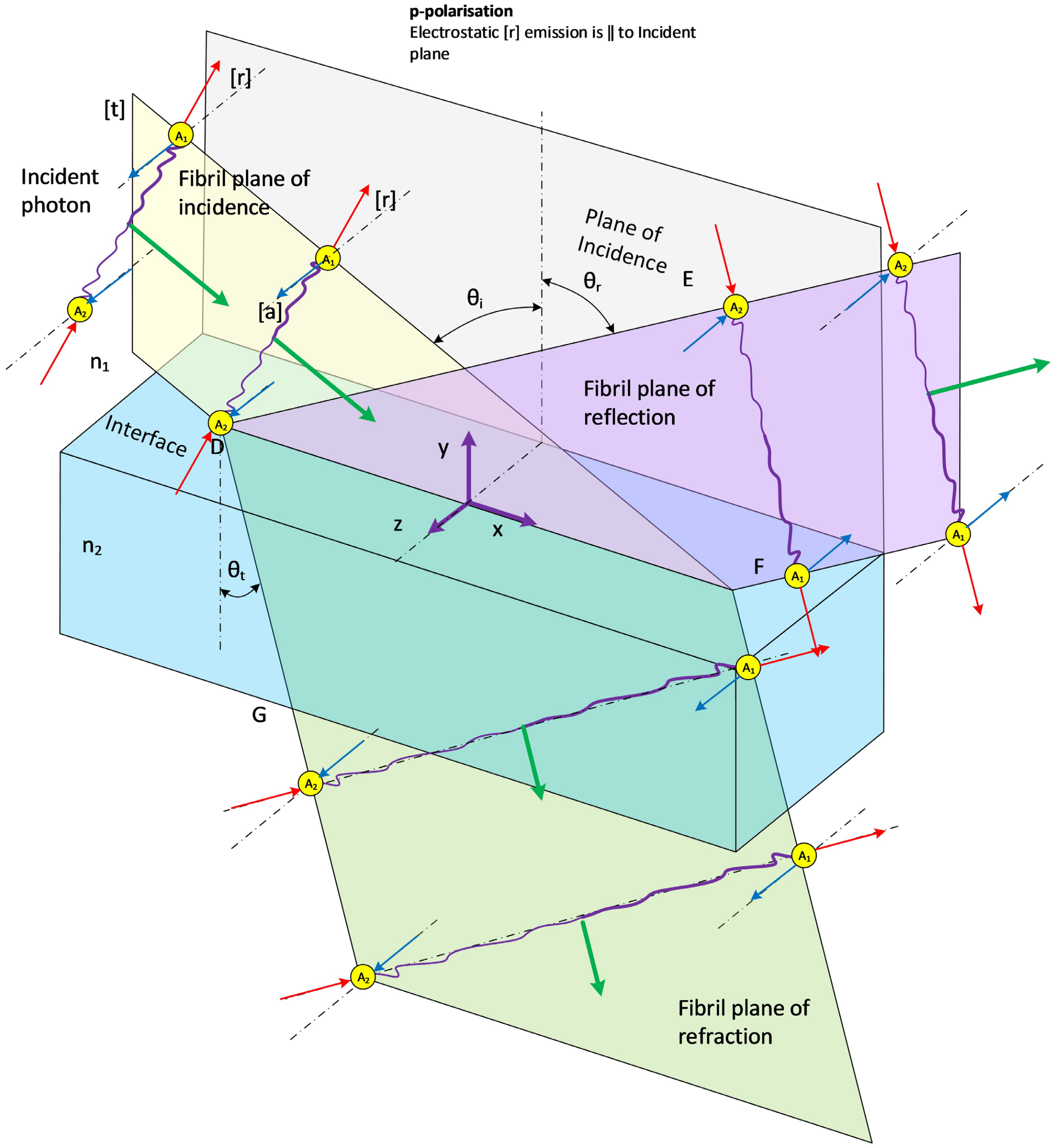

Figure 14. Orientation and locus of Cordus photon for p-polarisation for Fresnel derivation.

the Cordus energisation sequence [*a*]->[*r*]->[*t*] and the right hand rule gives the photon moving in direction [*a*], the reactive end energising radially outwards [*r*] and corresponding to the E field, and [t] being the direction of the B field. This uniquely identifies the directions of the E and B field.

Second, accept the conventional requirements for field continuity, on the basis that they represent the sum of the forces acting on the electron(s) on the interface. The governing relationship is based on minimising the sum of the electron motions, rather than conservation between input and output fields. Hence the requirements for field continuity in p-polarisation are

$$E_{ix} + E_{rx} = E_{tx} \tag{15}$$

and

$$B_{zi} + B_{zr} = B_{zt} \tag{16}$$

and these correspond to components of emissions in the [*r*] and [*t*] directions respectively. The vector components in the *x* direction depend on the phase status at reflection, *i.e.* whether reflecting off a denser or less dense medium, see Figure 15.

Derivation of reflection and transmission coefficients

For reflection off a denser medium, phase change occurs at reflection, and assume both *E* and *B* flip, see Figure 15(a). The electric field continuity in the plane of the interface is:

$$E_i \cos\theta_i + E_r \cos\theta_r = E_t \cos\theta_t \tag{17}$$

where $\theta_i = \theta_r$ by the law of reflection.

The magnetic field continuity is:

$$\frac{B_i}{\mu_1} - \frac{B_r}{\mu_1} = \frac{B_t}{\mu_2} \tag{18a}$$

in which assume $\mu_1 = \mu_2$, and put $n_1 E_i \propto B_i$ etc., rearrange for E_t:

$$n_1 E_i - n_1 E_r = n_2 E_t$$

$$E_t = \frac{n_1}{n_2}\left(E_i - E_r\right) \tag{18b}$$

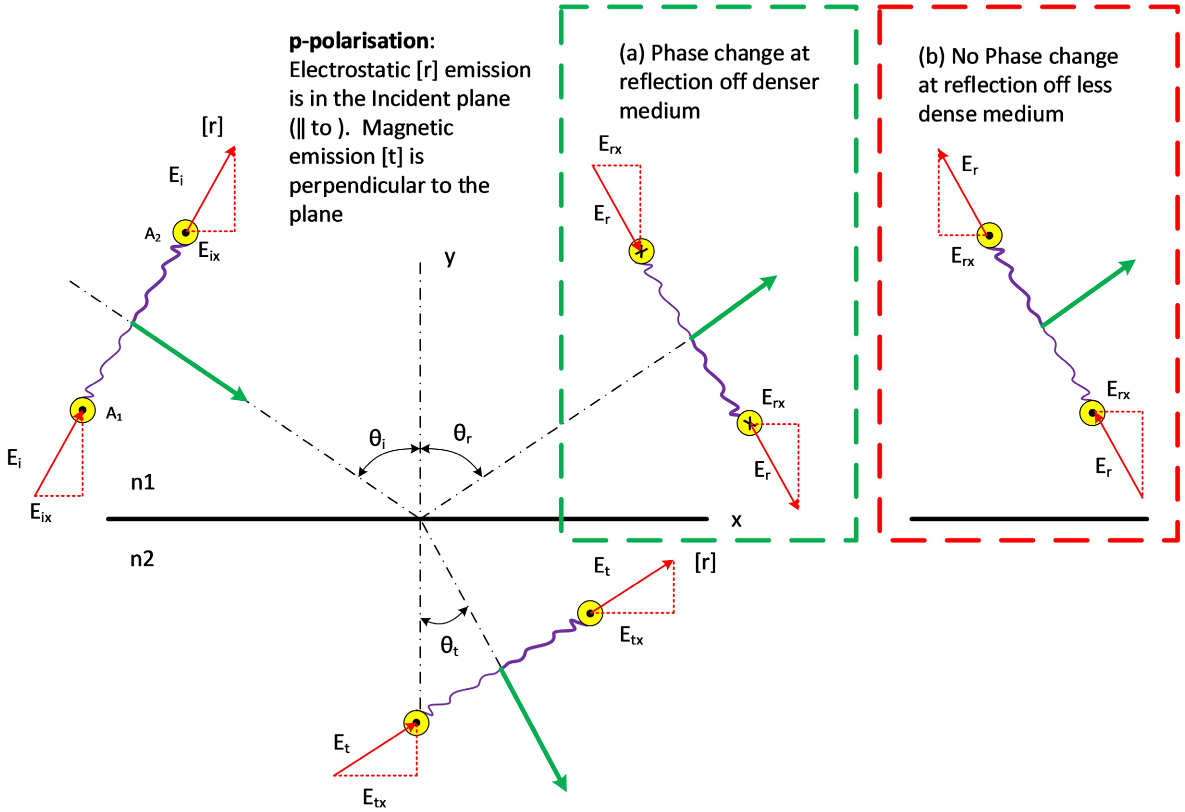

Figure 15. Emission structures for photon polarised parallel to the incidence plane (p-polarisation).

and substitute Equation (18b) into the electric field Equation (17), hence

$$E_i \cos\theta_i + E_r \cos\theta_i = \frac{n_1}{n_2}\left(E_i - E_r\right)\cos\theta_t \tag{19}$$

which may be re-arranged for E_r/E_i giving the reflection coefficient:

$$r_p = \frac{E_r}{E_i} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \tag{20}$$

For the transmission coefficient, rearrange Equation (18b) to make E_i the subject, substitute into the electric field Equation (17), and re-arrange for $\frac{E_t}{E_i}$ giving:

$$t_p = \frac{E_t}{E_i} = \frac{2n_1 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \tag{21}$$

These are identical to the conventional Fresnel equations derived from wave theory.

For reflection off a less dense medium, there is no phase change at reflection, and **Figure 15(b)** applies. The electric field continuity in the plane of the interface becomes:

$$E_i \cos\theta_i - E_r \cos\theta_r = E_t \cos\theta_t \tag{22}$$

The magnetic field continuity is:

$$\frac{B_i}{\mu_1} + \frac{B_r}{\mu_1} = -\frac{B_t}{\mu_2} \tag{23}$$

Applying the same assumptions and rearrangements as before gives Equation (20) and Equation (21) again, as expected. This confirms that the method works for reflection off both denser and less-dense media.

Fresnel equation for s-polarisation

Physical interpretation

Here the electric field is transverse to the incident plane, and the magnetic field is in that plane, see **Figure 16**. The photon fibril is perpendicular to the incidence plane. Consequently, both reactive ends A and B engage simultaneously with the surface of the new medium. As before, we assume that the interaction with the surface involves each reactive end of the photon interacting with electrons, where those electrons become entangled during the interaction.

For reflection off a denser material, $n_1 < n_2$, the photon is momentarily absorbed and then re-emitted, with the change in phase appearing as an inversion of location of the reactive ends.

Derivation of reflection and transmission coefficients

The electric field continuity in the plane of the interface is:

$$E_i + E_r = E_t \tag{24}$$

The magnetic field continuity is:

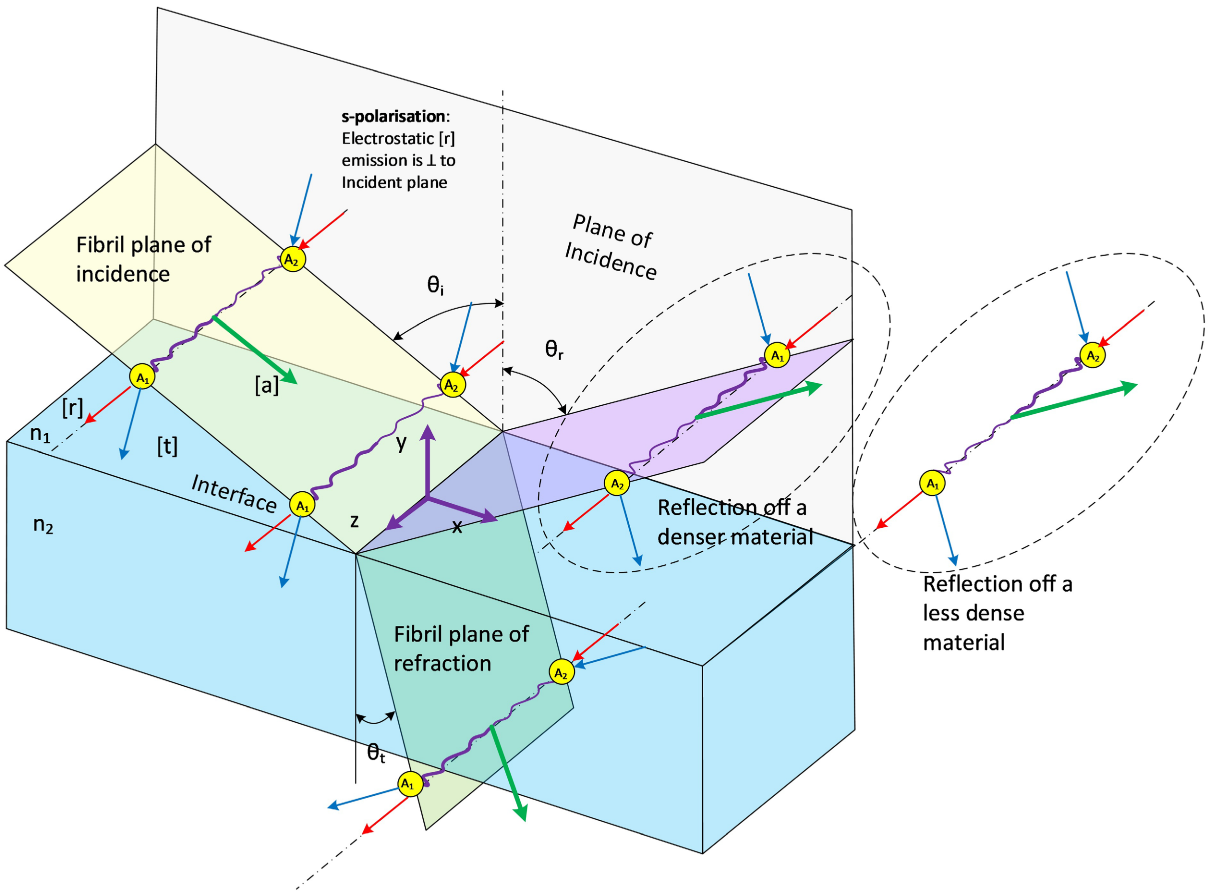

Figure 16. Emission structures for s-polarisation.

$$\frac{-B_i \cos\theta_i}{\mu_1} + \frac{B_r \cos\theta_r}{\mu_1} = \frac{-B_t \cos\theta_t}{\mu_2} \tag{25a}$$

where $\theta_i = \theta_r$ by the law of reflection. Assume $\mu_1 = \mu_2$, and put $n_1 E_i \propto B_i$ etc., rearrange Equation (25a) for E_t:

$$\left(n_1 E_i \cos\theta_i - n_1 E_r \cos\theta_i\right)\frac{1}{n_2 \cos\theta_t} = E_t \tag{25b}$$

and substitute Equation (25b) into the electric field equation Equation (24), giving

$$E_i + E_r = \left(n_1 E_i \cos\theta_i - n_1 E_r \cos\theta_i\right)\frac{1}{n_2 \cos\theta_t} \tag{26}$$

which may be re-arranged for E_r/E_i giving the reflection coefficient:

$$r_s = \frac{E_r}{E_i}\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \tag{27}$$

For the transmission coefficient, redo the rearrangement for E_i and E_t, giving

$$t_s = \frac{E_t}{E_i} = \frac{2n_1 \cos\theta_i}{n_1 \cos\theta_i + n_2 \cos\theta_t} \tag{28}$$

Equations (27)-(28) are identical to the conventional Fresnel equations derived from wave theory and complete the demonstration of derivation from a particle perspective.

For reflection off a denser material, $n_1 > n_2$, the interpretation is that the photon is simply reflected rather than absorbed and re-emitted, and there is no change in location of reactive ends. Functionally the directions of the electric and magnetic fields are as before and hence the same derivation Equation (24)-(28) applies.

Derivation of reflectivity and transmissivity

The reflectivity power ratio is determined as the square of the reflectivity coefficient. The squared relationship between electric field and energy in this theory is motivated per [19].

Reflectivity for s-polarisation, is determined from Equation (27):

$$R_s = \left(\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right)^2 \tag{29}$$

Reflectivity for p-polarisation from Equation (20):

$$R_p = \left(\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right)^2 \tag{30}$$

The transmissivity power ratio is $T = 1 - R$ by energy conservation.

For *s* polarisation, with substitution of the transmission coefficient:

$$T_s = \frac{n_2 \cos\theta_t}{n_1 \cos\theta_i} t_s^2 \tag{31}$$

And likewise for p polarisation

$$T_p = \frac{n_2 \cos\theta_t}{n_1 \cos\theta_i} t_p^2 \tag{32}$$

These are the same outcomes as the conventional derivation via electromagnetic wave theory, but here from a particle basis.

6. Discussion

Findings

Validation is provided by the particle theory producing Fresnel equations with identical structure to those produced by electromagnetic wave theory. This paper makes several novel contributions to the theoretical understanding of single-photon optics. First, it provides a quantitative derivation of the Fresnel equations for a single photon particle, which has not previously been shown in the literature. These derivations include p and s-polarisation, internal and external reflection. Second, it proposes descriptive explanations for the principles and mechanisms that underlie the Fresnel equations. These mechanisms are based in plausible physical reality, and do not require special assumptions, exceptions, new particles, or navigational intelligence within particles. This is an ontological contribution. Third, the paper proposes the mechanisms for other optical phenomena including polarisation, refraction and reflection, and it recovers Snell's law too. Consequently it provides a comprehensive particle-based derivation and physical explanation of the basic optical laws.

Limitations

A derivation of the reflection and transmission coefficients for p- and s-polarised light is given. However a limitation is the lack of a full explanation for the navigation question: what determines whether an individual photon takes the reflection or refraction pathway? A preliminary tentative explanation is given in terms of energization state (phase angle), based on analogous work on beam splitters [38]. This is an area for potential future elaboration by theory. In addition it is desirable to see new experimental work on behaviour of individual photons in the Fresnel setting, as the literature is sparse (for an exception see [39]).

A test for falsifiability is that the theory predicts the photon is absorbed and re-emitted for reflection off a more dense medium (**Figure 12**), but is not absorbed for reflection off a less dense medium (**Figure 13**).

Another limitation of the paper is the lack of an overarching mathematical formulation for the Cordus theory. There are components of mathematical formulation available [19] [20] [26]. Furthermore the theory has a strong logical coherence in terms of its lemmas and principles, as demonstrated in its breadth of applicability [1] [19]-[32] [38] [40]-[49]. However it is acknowledged that a complete mathematical formulation has not yet been achieved. Consequently, from a mathematical perspective, the self consistency of the theory is less explicit than ideal. The difference is particularly apparent when compared to quantum theory with its strong and well-develop mathematical representation. Hence a potential area of future research is the development of a comprehensive mathematical representation of the theory.

Implications for future work

The current work only deals with optical surfaces in bulk. There are many other related areas of more complex cases. Examples include multilayer optical structures [50], thin films, crystalline heterostructures [6], micro optic waveguides [51], conductors or semiconductors, excited surfaces (e.g. plasmons) [52], scattering [53], and microscopic theory of electromagnetic materials [4]. These areas have their own well-developed methods, or are developing them, based on refinement of the basic Fresnel equations from 200 years ago. These approaches use mathematical theory-building and modelling.

A potential area for further development of this theory—and optical theories in general—is to the provision of a mechanics that can predict the optical properties of molecular and crystalline structures, which is to say the design of molecules for specific optical properties. This is currently an active research field [54], but is mostly empirical. The molecular structure, specifically the bonds, provides the underlying mechanism for photoluminescent hybrids and synthesis routes exist e.g. for gold nanoclusters [55] and aggregates of a building block molecule [56]. Polymerisation of organic molecules induces changes in optical properties, e.g. photoluminescence [57], and the inverse has also been shown in photomodulation of molecular structure [58]. Exact solutions to Maxwell's equations have been developed for dye layers [59], though simplifications were required that imply this may be a difficult route for more complex structures. Another route is computational evaluation of given structures, e.g. for carbon allotropes [60], though this requires the structures be at least partly predefined. Molecules have been designing for optical properties using search optimisation [61], currently limited to one dimensional molecular aggregates. On the whole the existing approaches are mainly empirically, the underlying photon mechanisms at the electron level are poorly understood, and design ability is limited to variants of a particular molecule. Hence there is value in developing a comprehensive theory of the interaction of photons with molecular and crystalline structures, and how this causes optical behaviours to arise.

Implications

This paper shows that all the main optical laws may be derived from a particle basis. The wave nature of light is still accommodated, as a series of particles. This implies philosophically that the concept of wave-particle duality, *i.e.* the incompatibility of the continuum and quantum interpretations of light, is unnecessary. It has long been suspected that a deeper physics might exist that resolves wave-particle duality. This work shows that such a theory is indeed conceivable.

Philosophically, what is it that makes the Cordus particle theory able to explain optical laws? The answer appears to be in the way the Cordus theory provides for discrete electric and magnetic fields, since these—and their orientations—are key in the Fresnel derivations. In turn these fields –both their identity and their spatial orientation—arise naturally from consideration of the discrete field emissions and substructure of the Cordus particle. In contrast quantum particles have attributes of spin, charge, etc., but these have no physical meaning, nor does quantum theory explain why electric and magnetic fields would be specifically oriented and orthogonal. In contrast, electromagnetic wave theory intrinsically provides for such fields, but is unable to explain how these arise and it makes no accommodation for single particles. The Cordus theory bridges over these problems.

7. Conclusions

The objective of this work was to derive the basic optical laws from first principles from a non-local hidden-variable particle basis. In this theory, the photon substructure comprises two reactive ends some distance apart and connected by a fibril, with the reactive ends emitting directional fields in the form of the electrostatic and magnetic fields. These fields are in-phase (cis-phasic) and orthogonal. This provides a physical explanation for polarisation, as alignment of the electrostatic field with a specific direction. This direction arises either at the time of emission from another particle (e.g. electron) that also has a linear substructure, or during transmission by imposition of the crystalline structure of the medium.

The idea that the photon has a span, defined by its two reactive ends, is used to derive Snell's law and the critical angle. The proposed physical substructures result in efficient derivations of only a few steps, with an accompanying ontological explanation. Similarly, the Fresnel equations are derived from first principles with this theory, for both s and p polarisations. Hence this paper shows that all the main optical laws may be derived from a NLHV particle basis.

This is significant because the same theory also extends into aspects of cosmology—for example it provides an explanation of asymmetrical baryogenesis by predicting a process whereby antielectrons could be remanufactured into protons with the emission of neutrino species as a waste product [44], it derives an expression for gravitation that recovers Newtonian gravitation while also identifying a deeper dependence of gravitational on the temporal and spatial evolution of the universe, and it derives the Lorentz and relativistic Doppler formulation from first principles. Furthermore, the theory extends into particle physics in the way it provides a physically natural explanation for wave-particle duality in the double slit [1] and interferometer [38], it derives the electron g factor g = 2 from first principles [27], it predicts the stability/instability/non-existence of all nuclides H-Ne [45], and it unifies the interactions by explaining them to be different aspects of the field emissions [25]. Now the same theory has been extended to encompass conventional optical laws, which have not previously been explained from a particle basis. Most of the above phenomena have explanations and derivations from one or other theory of physics—the exceptions being asymmetrical baryogenesis and nuclide stability—however, the intellectual novelty here is explaining them all from one theory of physics. The broader philosophical implication is that a theory now exists—at least conceptually though not yet complete in its mathematical formulation—that shows a way to a deeper physics that accommodates other ways of thinking about physics such as quantum mechanics, general relativity, and wave theory.

Conflicts of Interest

The author declares that there are no financial conflicts of interest regarding this work.

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