Explanation of photon navigation in the Mach-Zehnder interferometer

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Abstract

***PROBLEM**: Photon path dilemmas in interferometers manifest as an apparent ability of the photon to simultaneously take all paths through the device, but eventually only appear at one output. **OBJECTIVE**: This paper applies a non-local hidden-variable (NLHV) solution, in the form of the Cordus theory, to explain photon path dilemmas in the Mach-Zehnder (MZ) interferometer. **FINDINGS**: The partial mirrors function as tunnelling devices, that allow the photon structures to be directed to different loci hence legs of the apparatus, depending on the energisation state of the photon. Explanations are provided for a single photon in the interferometer in the default, open-path, and sample modes. The apparent intelligence in the system is not because the photon knows which path to take, but rather because the MZ interferometer is an unexpectedly finely-tuned photon-sorting device that auto-corrects for randomness in the frequency phase to direct the photon to a specific detector. The principles also explain other tunnelling phenomena involving barriers. **ORIGINALITY**: The originality is explaining path dilemmas in the MZ interferometer in terms of physical realism, and from a NLHV perspective. **IMPLICATIONS**: The physics of optics at the next lower fundamental level are theorised to be based on the photon having internal structures. This has the potential to provide new understanding of photon behaviour in theoretically challenging situations*.

Keywords: wave-particle duality; interferometer; tunnelling

1 Introduction

There are various path problems and paradoxes in wave-particle duality. Typical situations are the double-slit device and interferometers. The problem manifests as an apparent ability of the photon to simultaneously take all paths through the devices, but eventually only appear at one outlet. This is a difficult area for classical physics, and even quantum mechanics only partially explains the phenomena. This paper extends previous work [1] by applying a non-local hidden-variable (NLHV) solution, in the form of the Cordus theory [2], to explain photon path dilemmas. The application is primarily to the Mach–Zehnder interferometer, although the principles generalise to explain tunnelling.

2 Existing approaches

Wave theory explains the situation as interference of two waves. However, that only applies to beams of light, whereas the empirical reality is that the behaviour also exists for individual photons. Classical wave theory cannot explain this. Quantum mechanics (QM) offers a quantitative solution for the particle case, using the concepts of superposition and wave function. The ideas of wave function and probabilistic superposition are intrinsically mathematical, and attempts to translate these into physical mechanisms have not fared well. For example, the explanation that relies on virtual (or ghost) particles only adds more problems, because of the undetectability of these particles. Hence the explanations are inconsistent with physical realism, and an ontologically satisfactory explanation has been elusive. Physical realism is the assumption, based on experience in the everyday world, that observed phenomena have underlying physical mechanisms [3]. From this perspective both classical and quantum physics are incomplete descriptions of photon path behaviour, despite having acknowledged strengths in other respects.

Other explanations for the path dilemma in wave-particle duality are intelligent photons and parallel universes, but both have difficulties. The first assumes some intelligence in the photon: that photons know when a path is blocked, without even going down it (e.g. Mach-Zehnder interferometer), and adapt their behaviour in response to the presence of an Observer (e.g. Schrodinger's Cat, Zeno effect). This also raises philosophical problems with choice and the power of the Observer to affect the physical world and its future merely by looking at it (contextual measurement). Thus the action of observation would affect the locus taken by a photon, and thus the outcome. This concept is sometimes generalised to the universe as a whole. The second explanation is the metaphysical idea of parallel universes or many worlds, i.e. that each statistical outcome that does not occur in this universe does in another [4]. It is fundamentally problematic -from the perspective of physical realism - that these other universes are beyond contact. It also means the theory cannot be verified. Nor is it clear what keeps track of the information content of the vast number of universes that such a system would generate. Both these explanations are convenient ways of comprehending the practicalities of wave-particle duality, but they sidestep the real issues.

Finally, there is the hidden variable sector of physics. This is based on the assumption that particles have internal sub-structures that provide the mechanisms for the observed behaviours. Although this principle is consistent with the expectations of physical realism, the sector as a whole has been unproductive at developing useful theories. There was a historical attempt to explain path dilemmas assuming hidden-variables, in the form of the de Broglie-Bohm theory of the pilot wave [5] [6]. However it is debateable whether this really solves the problem. Nor has the concept progressed to form a broader theory of physics that could explain other phenomena.

Thus none of the theories of physics provide an adequate explanation of path dilemmas. Wave theory and QM provide the best descriptors, but even so are incomplete and incompatible with each other. There is a need to consider whether the phenomena may be better explained from other perspectives.

One such alternative approach is the Cordus theory. This theory is a type of non-local hidden-variable (NLHV) theory, and therefore has an explicit link between the functional attributes of the particle and a proposed inner causality. For the origin of this NLHV concept and its application to the double-slit device, see [2]. The resulting particle structure was then used to explain other phenomena. A derivation of optical laws (reflection, refraction and Brewster's angle) from a Cordus particle perspective was achieved [2]. This theory explains many other aspects of photon behaviour at a fundamental or cosmological level, including the processes of photon emission and absorption [7, 8], conversion of photons to electron-positron in pair production [9], annihilation of matter-antimatter back to photons [10], the asymmetrical genesis production sequence from photons to a matter universe [11], and origin of the finite speed of light [12]. The theory is applicable to physics more generally, and has been used to derive the electron g factor (g=2) which otherwise only quantum mechanics can do, and the relativistic Doppler and the Lorentz factor [13], which is otherwise the preserve of general relativity. Consequently the NLHV sector has now become productive again, and it is worth further exploring its ability to explain optical phenomena.

3 Approach

The purpose of this work was to apply the Cordus theory to the photon path problem in interferometers.

The approach taken was a conceptual one. Engineering design principles were used to logically infer the requisite internal structures and their properties, that would be sufficient to explain the observed path phenomena. Assumptions were represented as a set of explicit lemmas. The area under examination is the Mach-Zehnder (MZ) interferometer.

4 Results

4.1 Underpinning concepts

The Cordus theory predicts a specific internal structure for fundamental particles. This comprises two reactive *ends* some spatial distance apart and connected by a fibril. The reactive ends are energised at a frequency, and emit discrete forces at these times [2]. This is a NLHV structure but with discrete fields. This is very different to the zero dimensional (0-D) point construct of QM. The structure of the photon is shown in Figure 1, and for comparison the electron in Figure 2.

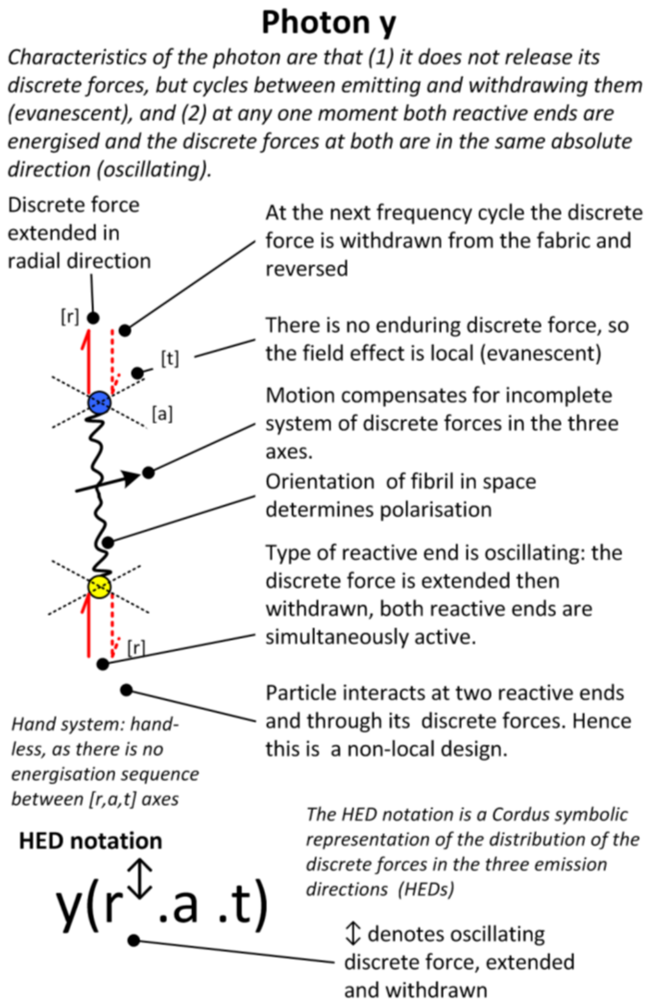

Figure 1: Cordus theory for the internal structure of the photon, and its discrete field arrangements. The photon has a pump that shuttles energy outwards into the fabric. Then at the next frequency cycle it draws the energy out of that field, instantaneously transmits it across the fibril, and expels it at the opposite reactive end. Image [14].

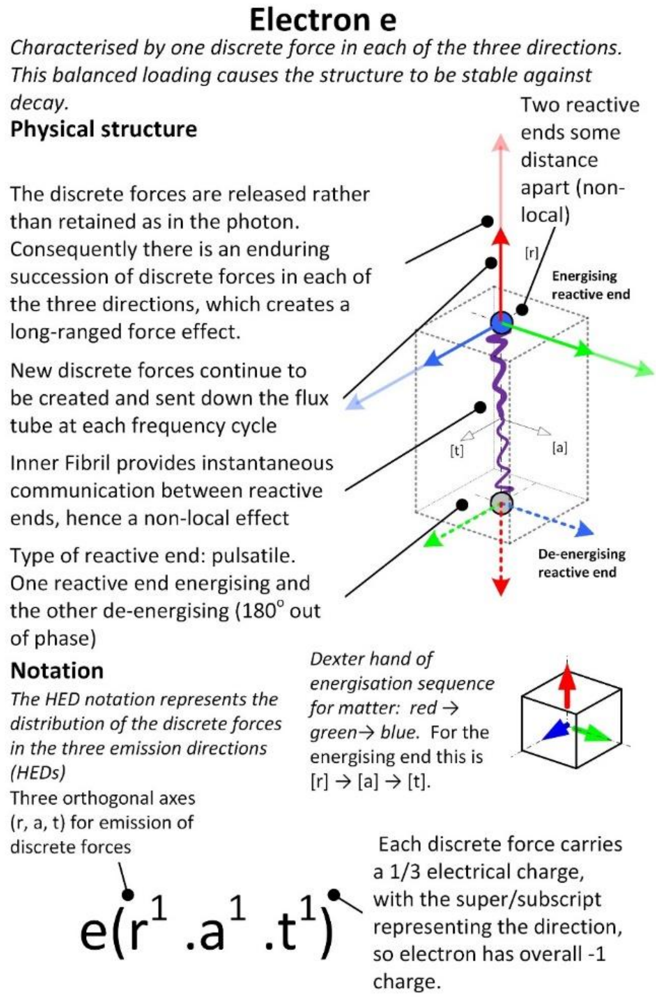

Figure 2: The representation of the electron's internal and external structures. It is proposed that the particle has three orthogonal discrete forces, energised in turn at each reactive end. Adapted from [15].

The theory requires the photon to have an oscillating system of discrete fields. The discrete forces are ejected from one reactive end and (at the same moment) drawn in at the other. At the next stage in the frequency cycle the directions reverse. Consequently the photon's discrete forces are recycled. This also explains why the evanescent field weakens exponential with distance: because the discrete forces recruit a volume of space [7]. In contrast massy particles such as the electron emit discrete forces (the direction provides the charge attribute) and release them into the external environment in a series making up a flux tube. Hence the electric field has an inverse radius squared relationship: because it progresses outwards as a front on the surface of an expanding sphere. The sign convention is for outward motion of discrete forces to correspond to negative charge, and inward to positive. Consequently this structure also explains why the electric field of the photon reverse sign.

The explanation of the double-slit experiment is briefly summarised as follows from [2]. Each reactive end of the photon particle passes cleanly through one slit. The fibril passes through the material between the two slits, but does not interact with it. The particle structure collapses when one of the reactive ends encounters a medium that absorbs its discrete forces, and the whole photon energy then appears at this location. Consequently whichever reactive end first encounters a detector behind the double-slit device, will trigger a detection event. If there is a detector behind each slit, then the variability of the photons' phase offset results in the events being shared across the detectors. Hence a single photon appears at one or the other slit, but a stream of them looks like a wave.

However when only one slit has a detector, then the photon always appears there. This is explained as one of the two reactive ends of the particle passing through each slit, as before. Then the whole particle collapses at whichever reactive end first grounds, and this is always the detector since it is first in the locus. No photon structure travels beyond the detector, so no fringes appear on the screen beyond the detector in this case.

4.2 Mach–Zehnder interferometer

Quantum dilemmas also arise in the Mach–Zehnder interferometer. This device has two output paths, hence two detectors, see Figure 3. The light source strikes partial mirror PM1, where the beam is split into paths 1 and 2, the two beams recombine at partial mirror PM2, and then proceed to detectors DA and DB. However there are some anomalous results, especially for single photons, described below.

MZ Default mode

In the default mode the photon, and indeed the whole beam, will selectively appear at one of the detectors. This can easily be explained using conventional optical wave theory. The paths are not identical regarding the reflection and refraction encountered, and the usual explanation is based on the delays, i.e. phase shift in wavelength, for the different reflection and refraction on the two paths.

From the wave theory perspective the explanation is that the light beam experiences a phase shift of half a wavelength where it reflects off a medium with higher refractive index (otherwise none), and a constant phase shift k where it refracts through a denser medium.

The beam on path 1 to Detector DB experiences k + ½ + ½ phase-shift (at a, c, and e), see Figure 3, whereas to reach Detector DA requires an additional k (at y). Similarly, the beam on path 2 to Detector DB experiences ½ + ½ + k (at p, r, and t). As these are the same, the classical model concludes that the two beams on 1 and 2 result in constructive interference at DB, so the whole output appears there, providing that the optical path lengths around both sides of the interferometer are equal. Similarly, the 2 beam into Detector DA experiences ½ + ½ + k + k phase-shift (at p, r, t, and v) whereas the 1 beam into DA experiences k + ½ + k phase-shift (at a, c, v). As these differ by half a wavelength, the usual explanation is that the two beams interfere destructively and no light is detected at DA.

This provides a satisfactory explanation for continuous light beams, though not for single photons.

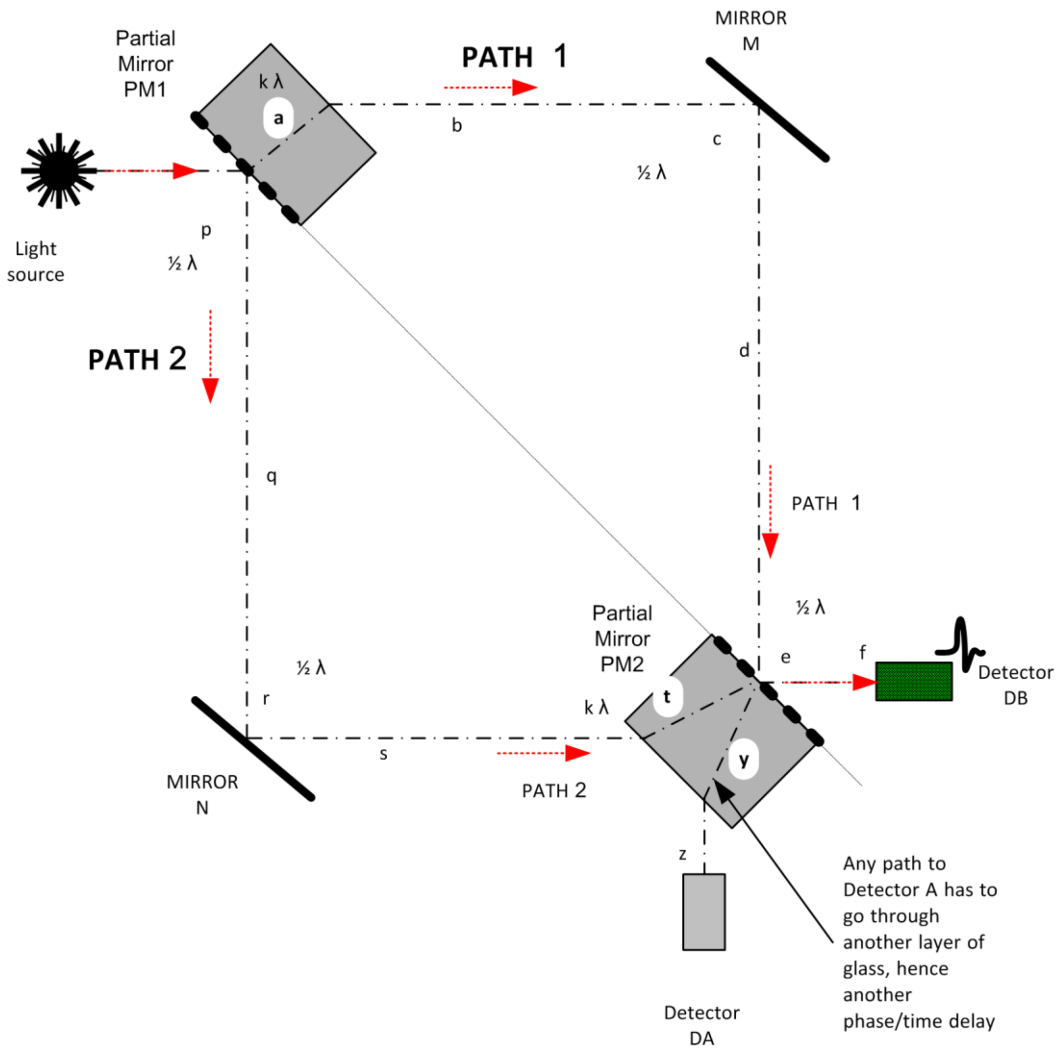

Figure 3: Mach–Zehnder interferometer in default mode. The photon appears at DB.

Quantum interpretation

The quantum weirdness arises because this behaviour still occurs for a single photon, which is supposed to go down only one path. Thus self-interference seems to be required, or virtual particles. Worse, if one of the paths is blocked by a mirror that deflects the beam away, then the beam still appears at DB, regardless of which path was blocked. The photon seems to 'know' which path was blocked, without actually taking it, and then take the other. Quantum mechanics can quantify these outcomes and represent them mathematically, but does not offer an explanation consistent with physical realism.

4.3 Cordus explanation of MZ interferometer behaviour

A simplistic, and wrong, explanation would be that each reactive end (RE) of the Cordus particle takes a different path, and the phase difference through the glass at y means that the reactive end is delayed at Detector DA, so does not appear there. Assuming that each reactive end has a 50% chance of being reflected at a partial mirror, then the phase delay through the glass at y means that the reactive end gets to detector DB before DA. However this is unsatisfactory because a decision tree of the path options shows that ¼ of photons should still appear at DA even if DA is precisely located relative to DB. Some additional mechanisms must be at work if the theory is to be true to empirical observation. The solution is to add the following lemmas to the Cordus theory as published at [2].

Lemmas for photon engagement with a partial mirror (beam-splitter)

These lemmas describe a set of assumptions for how a beam-splitter operates. The lemmas are effectively a set of assumptions about the interaction between the reactive ends of a Cordus particle, and a continuous optical medium. As such the lemmas are based on the Cordus theory and internally consistent with all other parts thereof, including for example the cosmology parts.

1 In a usual full-reflection, i.e. off a mirror, both reactive ends of the photon particle, which are separated by the span, independently reflect off the mirror.

2 Reflection does not collapse the particle, i.e. the photon is not absorbed but rather continues on a locus.

3 When encountering a partially reflective surface, e.g. a beam-splitter or partially silvered mirror, the outcome depends on the state (energised vs. dormant) of the reactive end at the time of contact. Specifically:

- .1 A reactive end will reflect off a mirror only if it is in one state, nominally assumed to be the energised state, when it encounters the reflective layer.
- .2 A dormant reactive end passes some way into a reflective layer without reacting. Only if it re-energises within the layer will it be reflected.
- .3 If the reflective layer is thin enough, a dormant reactive end may re-energise on the other side of layer, in which case it is not reflected. Hence the reactive end tunnels through the layer, and re-energises beyond it.
- .4 The thickness of the layer is therefore predicted to be important, relative to the displacement in space that the reactive end can make. The latter is determined by the velocity and frequency of the particle.

4 The orientation of the particle, i.e. polarisation of a photon or spin of an electron, as it strikes the beam-splitter is important in the outcome.

- .1 If the reactive ends strike at suitable timing such that each in turn is energised as they engage with surface, then the whole particle may be reflected. Likewise if both reactive ends are dormant at their respective engagements, then the whole particle is transmitted.
- .2 It is possible that only one reactive end is reflected and the other transmitted straight through. In this case the beam-splitter changes the span of the photon. This is explored further below.

5 The span of a photon is not determined by its frequency. (For massy particles, e.g. electron, span and frequency are related.)

- .1 The photon span is initially determined at its original emission per [7] but is able to be changed subsequently. The reactive ends follow the surfaces of any wave guides that might be encountered, and the span may change as a result. This has no energy implications for the photon.
- .2 In contrast the electron and other massy particles have a span inversely related to the frequency and hence to the energy.

These principles are summarised in Figure 4.

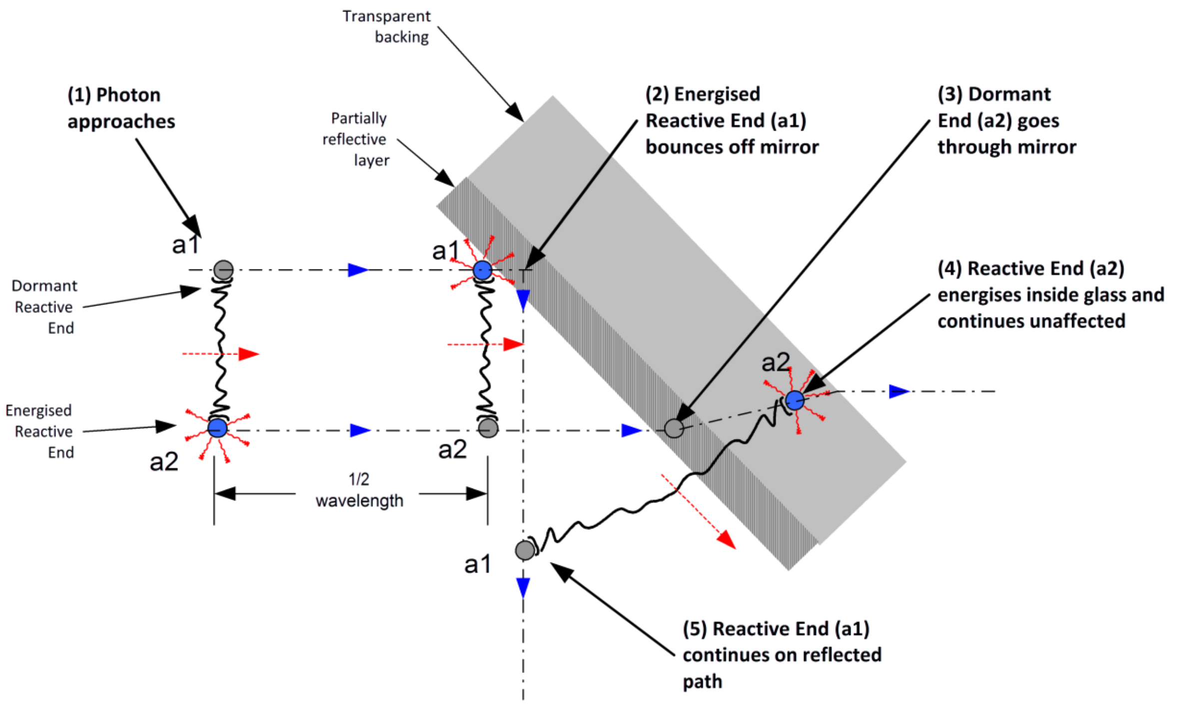

Figure 4: A beam-splitter reflects only the energised reactive end. The dormant reactive end passes through. The diagram shows a p-polarised photon, but the principles generalise to other forms of polarisation. The key determinant of path is the state (energised/dormant) of the pair of reactive ends at contact with the mirror.

The lemmas identify the variables and the mechanisms that determine which path the exit light takes. The implication is that a reactive end reflects if in a suitably energised state at the point of contact. Otherwise it goes deeper into the material. If by going deeper it passes through the reflective layer of the beam-splitter, then it continues without being reflected. Thus photons striking the beam splitter will have two obvious outcomes: both reactive ends reflect, or neither reflect (both transmit through). These outcomes depend on the orientation (polarisation) of the particle, the precise phase location of the energised reactive end when it makes contact, and the frequency relative to the thickness of the mirror. The lemmas also admit the possibility that the beam-splitter may reflect one reactive end and transmit the other, hence sending reactive ends on non-parallel paths and changing the span of the photon.

The lemmas also explain the variable output of the beam-splitter: with one input beam, generally two beams will be observed emerging from a beam-splitter. This may be explained as the variable orientations (polarisations) of the input photons ensuring that a mixture of whole and split particles will go down each path. Furthermore it is observed that if the polarisation of the input beam is changed then the beam splitter will favour one output, and this too is consistent with the above Cordus explanation.

Explanation of MZ interferometer in default mode

With these lemmas the Cordus explanation of the MZ device may now be continued. We consider a single photon, but the principles generalise to a beam of many. The photon reaches Partial Mirror PM1, see Figure 5. The energised reactive ends reflect off the mirror, the dormant ends go through. Depending on the polarisation and frequency states of the photons, some whole photons go down path 1, some down 2, and some may be split to go down both. The polarisation of the photon is therefore important in the outcome.

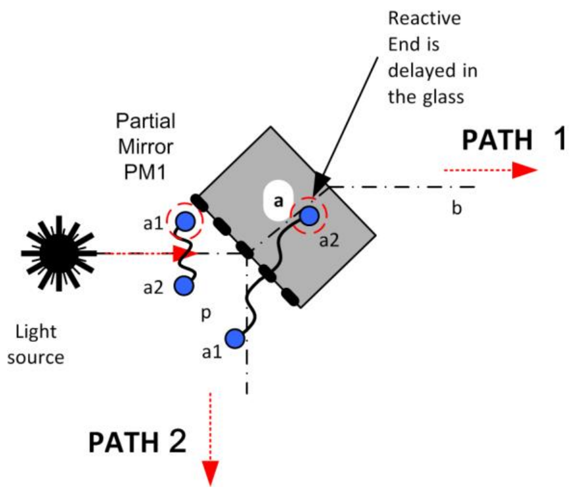

Figure 5: Photon particle interaction with the First partial mirror of the Mach-Zehnder interferometer.

The whole photons pose no particular problem, but a split photon needs explanation: a1 reflects off the surface and continues on path 2 (pqrst). The dormant a2 reactive end passes through the mirror surface, reenergises too late within the transparent backing, does not reflect, and continues on path 1 (abcd). Note that the order is unimportant: it is not necessary that the energised reactive end reaches the surface before the dormant reactive end. Nonetheless, regardless of the order, the reactive end that was energised at the mirror (a1 in this case), is always reflected (takes path 2). This is important in the following explanation. Assuming equal optical path length along 1 and 2, which is the case since the apparatus is tuned to achieve this, then both reactive ends come together again at Partial Mirror PM2, having undergone several frequency reversals.

The explanation assumes that the path length is such that the reactive ends at PM2 are all in the opposite state to PM1, i.e. the path lengths are not only equal, but a whole even multiple of half-wavelengths. The particles that have travelled whole down path 1 or 2 now divert to Detector DB. For the split particles the explanation follows: when reactive end a1 reaches the mirror surface of PM2 it is now in the dormant state, and therefore passes through to Detector DB. By contrast reactive end a2, which was dormant at PM1 is now energised at PM2, and reflects, taking it also to Detector DB, see Figure 6.

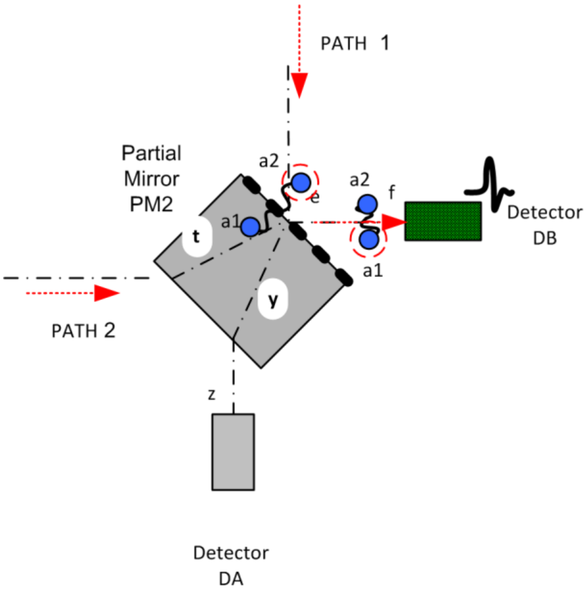

Figure 6: Photon behaviour at Second partial mirror of the Mach-Zehnder interferometer.

Therefore the photon always appears at Detector DB, regardless of which path it took. The partial mirrors achieve this by sorting and if necessary splitting the photons, and the arrangement between the mirrors ensures that the second mirror reverses the operation of the first. The effect holds for single photons and beams thereof. From this perspective the apparent intelligence in the system is *not* because the photons know which path to take, but rather because the MZ interferometer is an unexpectedly finely-tuned photon-sorting device that auto-corrects for randomness in the frequency phase.

The layout of an interferometer is usually taken for granted. The layout, e.g. MZ or other, is decided beforehand and the apparatus is tuned, by moving the components relative to each other, until the expected functionality is obtained. Consequently the layout is actually a set of additional covert variables which the observer (even if unknowingly) imposes on the experiment. This imposition limits the ways the apparatus can behave. The implications of the a-priori system design appear to be commonly overlooked.

MZ interferometer in open-path mode

Conventionally the wave-particle dilemma occurs when one of the paths is blocked, since it suggests the weird solution that photon ‘knew’ which path was blocked without actually taking it. For example, a mirror is inserted at S, but the photon still appears at Detector DB. Likewise a mirror at D still causes the photon to appear at Detector DB, see Figure 7, despite the apparent mutual exclusivity of these two experiments.

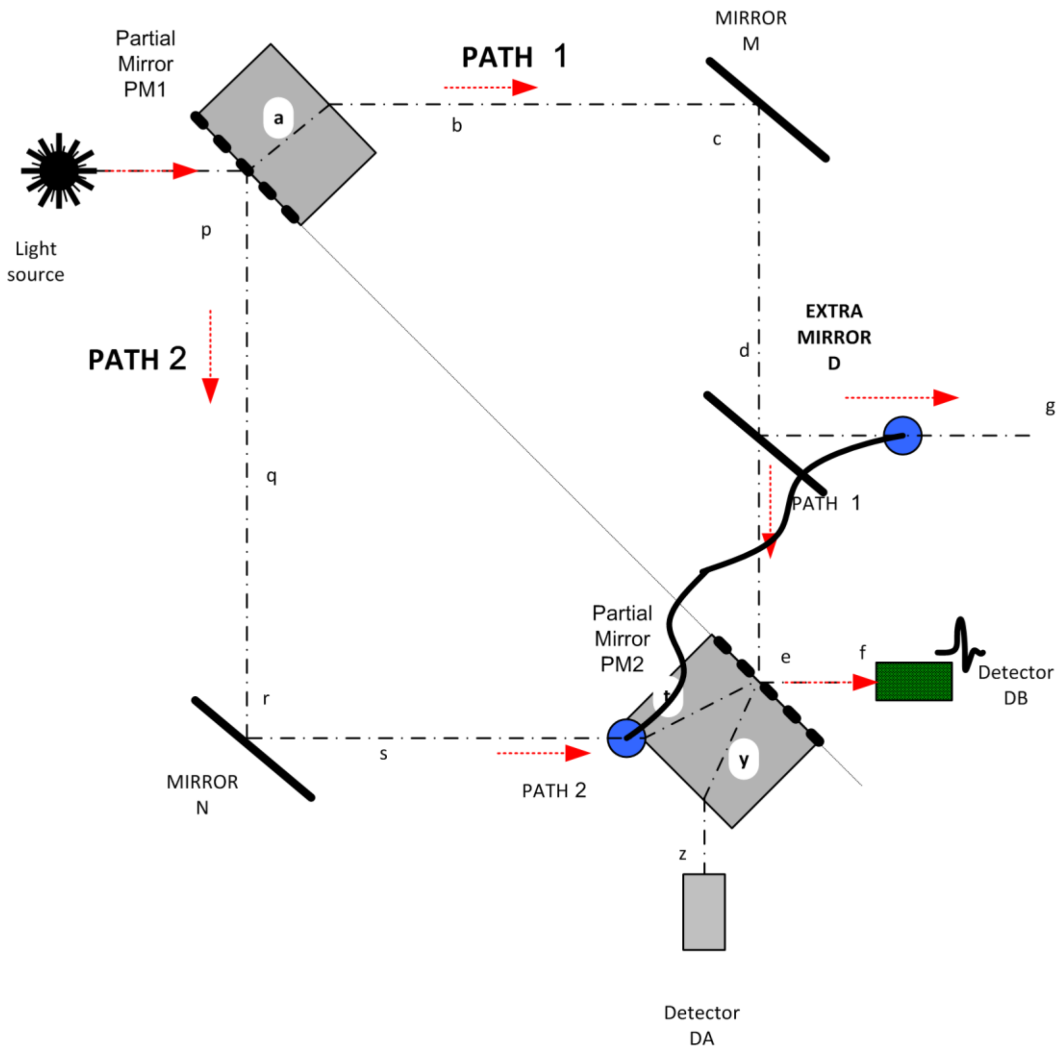

Figure 7: Inclusion of an extra mirror at D still results in photons arriving at Detector DB.

The Cordus explanation is that the reactive ends are constrained by the partial mirrors to converge at DB. Regardless of which path, 1 or 2, is open-circuited, the remaining whole particles and the split particles (providing they are not absorbed first at g) will always appear at DB.

MZ interferometer in sample mode

The MZ device may be used to measure the refractivity k_s of a transparent sample placed in one of the legs, say S. The observed reality when using a beam of photons is that a proportion of the beam now appears at detector DA. The wave theory adequately explains this based on phase shift and constructive (destructive) interference, but cannot explain why the effect persists for single photons.

The Cordus explanation is that the sample introduces a small time delay to the (say) a1 reactive end of the split particle, which means that it arrives slightly late at partial mirror PM2. If sufficiently late then a2 reaches the mirror in an energised state (it usually would be dormant at this point), and therefore reflects and passes to detector DA. If a2 is only partially energised when it reaches the mirror, then its destination is less certain: a single photon will go to one or the other detector depending on its precise state at the time. The proportioning occurs when a beam of photons is involved, as the random variabilities will place them each in slightly different states, and hence cause them to head to different detectors.

If the 1 or 2 path in the MZ device is totally blocked by an opaque barrier (unlike the mirror mode), then the whole particles in that leg ground there, as do the split particles. However the whole particles in the remaining leg continue to DB as before.

4.4 Explanation of tunnelling

An implication of the above is that the partial mirror (beam splitter) may be considered to operate on tunnelling effects. This is provided as an explanation for the photon behaviour at the partially silvered mirror (see lemma 3.3.). The same principles also explain other tunnelling phenomena involving a barrier. The 'barrier' could be a reflective surface, layers within prisms, or a non-conductive gap for electrons, e.g. Josephson junction.

The tunnelling effect is not explained by classical mechanics, but is by quantum mechanics. The typical QM explanation follows an energy line of thinking: the barrier requires a higher energy to overcome; the zero-dimensional particle is occasionally able to borrow energy from the external environment; it uses this to traverse the gap; the energy is then returned to the environment. The Heisenberg uncertainty principle provides the mechanism for the underlying indeterminism of energy. For QM, the randomness of tunnelling arises due to not all particles being able to borrow the necessary energy.

In contrast the proposed Cordus mechanism is that the reactive end of a particle does not react to the barrier when in the dormant state. If the dormant reactive end can completely traverse the barrier before re-energising, then it passes through the barrier. The other reactive end may likewise have an opportunity to do so, hence the whole particle may jump the barrier. The thickness of the barrier is a known detriment to tunnelling, and this is consistent with the Cordus explanation.

The Cordus concept of the fibril providing instantaneous co-ordination between reactive ends is also consistent with the observation that some tunnelling effects can be superluminal and non-local [16]. For the Cordus theory the randomness of tunnelling arises due to the variability of the particle's orientation and phase when it meets the barrier, and is not primarily an energy borrowing phenomenon. We thus make the falsifiable prediction that with suitable control of orientation and phase, it should be possible to get *all* incident particles to cross the barrier.

5 Discussion

Outcomes

We have shown that it is possible to give an explanation for the path dilemmas in the MZ interferometer, in its various modes, for single photons and beams. The results show that it is entirely possible to conceive of explanations based on physical realism. This does not require virtual particles, parallel worlds, pilot waves, intelligent photons, or any of the weirdness of conventional explanations. Nonetheless what it does require is physical structures at the sub-particle level, i.e. a non-local hidden-variable solution. Importantly while the solution requires some premises, these are not unreasonable and are not precluded by empiricism or other physics.

The work makes a number of original contributions. The first is achieving such an explanation in terms of physical realism. Optical wave theory cannot explain the behaviour of single photons, and quantum mechanics cannot do so within physical realism. A second contribution is fielding a solution from the NLHV sector, which has not previously been done. A specific internal structure of the photon has been put forward. While this theory is radical in that it proposes specific internal structures and discrete field arrangements for the photon, it is consistent with the empirical evidence that the photon field changes sign.

Another contribution is a new explanation for the principles of partial mirrors. This is that partial mirrors operate on partial tunnelling principles, and this also gives a physical explanation for tunnelling generally. This effect is otherwise only explainable using quantum mechanics, so an explanation from a NLHV basis is significant.

The capability of the wider Cordus theory is summarised in Table 1.

Table 1: Phenomena for which the Cordus theory has an explanation. Adapted from [17]

Phenomenon explained	**Abstract**	**Reference**
Wave-particle duality in the double slit device	One reactive end passes through each slit.	[2]
Derivation of optical laws from a particle perspective	Includes derivation of reflection and refraction laws, and Brewster's Angle from particle basis.	[2]
Prediction of particle structures	Electron, proton, neutron, neutrino species, photon	[15] [11] [18] [19] [14]
Explanation of the decay processes and prediction of a deeper decay model	Dependency identified on neutrino species loading	[18, 19]
Explanation for the selective spin characteristics of neutrinos whereby the direction of spin is correlated with the matter-antimatter species	Spin direction arises from reaction between incomplete discrete force emissions from the particle, and the background fabric.	[19]
Explanation for particle spin and derivation of the electron g factor g=2	Cordus particle structure naturally causes g=2	[17]
Explanation for the annihilation process	Description of the discrete force changes involved in remanufacture of these particle identities. Includes a conceptual explanation of the difference between otho- and para-	[10]

	positronium decay rates (ortho and para refer to spin combinations of the bound electron and anti-electron/positron).	
Provision of a mechanics for pair production	Rearrangement of discrete forces changes the particle identity.	[9]
Explanation of process of photon emission	Excess energy in the electron changes it span, which is opposed by bonding constraints.	[7, 8]
Synchronous interaction	Synchronous interaction between discrete forces of different matter particles causes the strong nuclear force	[20]
Predicted structure of atomic nuclei and explanation of stability for nuclides H to Ne	Protons and neutrons are arranged in a nuclear polymer. The rules for this arrangement, and for the bridge neutrons, are inferred and are qualitatively consistent with observed stability/instability/non-existence of all nuclides in this range.	[21, 22]
Prediction of a mechanism for asymmetrical baryogenesis	Predicts a decay path for remanufacture of the antielectron to the proton. This also solves the asymmetrical leptogenesis problem.	[11]
Origin of entropy	Fabric increases the Irreversibility of geometric position of particle.	[23]
A theory for time as an emergent property of matter rather than a universal attribute	Time arises from the interaction between the frequency of a particle and the local density of the fabric.	[24]
Nature of the vacuum and the cosmological horizon	Vacuum comprises fabric of discrete forces from massy particles.	[25]
Origin of the finite speed of light	Determined by fabric density, hence variable with epoch of universe and local distribution of mass.	[12]
Quantitative derivation of the relativistic Doppler and the Lorentz factor	Derivation accomplished from a particle perspective. Identifies fabric density as a covert variable.	[13]

Implications

The work demonstrates a new way to conceptualise fundamental physics than via the stochastic properties of 0-D points. Allowing particles to have internal structure yields explanations of interferometer behaviour and tunnelling. The wider implication is that the stochastic nature of quantum mechanics is interpreted as simplification of a deeper NLHV mechanics. The Cordus theory therefore provides a means to conceptually reconnect the mathematics of quantum theory to physical realism. Given that the Cordus theory spans diverse areas of physics (optics, particles, cosmology), which other theories struggle to achieve, it suggests the NLHV sector is not as barren as it seems.

Limitations

The major limitation of the theory is that its explanations are conceptual, and it does not yet have a mathematical formalism to represent the particle concept. This makes it difficult to represent the concepts, e.g. its explanations for the MZ interferometer behaviour, to the same level of quantitative detail that is available to quantum mechanics.

Future research opportunities

There is an opportunity for future research to develop a mathematical representation of the particle behaviour. This is a call for a novel mathematical approach, since there are multiple physical structures at the sub-particle level that need to be represented. There are also several empirical research opportunities. Once could be to test the tunnelling mechanism proposed here for the partial mirror, see also the falsifiable prediction above. Another could be to devise other ways of disrupting the MZ interferometer to test the proposal that the reactive ends of the photon occasionally go down different legs, i.e. the photon span is stretched to macroscopic dimensions. The Cordus theory is a proto-physics or candidate theory of new physics, and consequently there are also many possibilities for future research of a conceptual nature.

5 Conclusions

One of the central quantum dilemmas of the wave-particle duality is the ambiguity of where the photon is going, and which path it will take. Existing approaches either reconfigure the photon as a wave, or treat the problem as simply probabilistic. The present work suggests that the locus of the photon is determined by the orientation and frequency state of its reactive ends when they meet a partial mirror. Furthermore, it is proposed that each of the two reactive ends of the Cordus particle may take a different locus. Hence the theory is able to explain the behaviour of the Mach-Zehnder interferometer in its three modes: default-, open path-, and sampling-mode.

The Cordus theory provides a conceptual framework for how physical theory may be extended to levels more fundamental than currently reached by wave theory or quantum theory. This has the potential to provide new understanding of photon behaviour in unusual situations. In summary, the present results show that the Mach-Zehnder interferometer is an unexpectedly finely-tuned passive photon-sorting device that auto-corrects for randomness in the frequency phase. It behaves somewhat like a macroscopic optical meta-material.

Author Contributions

Authors of [1] contributed to the development of the idea for the Cordus particle, and the explanation for wave particle duality [2]. DP developed the explanations for the photon path dilemmas for the current paper.

Conflict of interest statement

The authors declare that there are no financial conflicts of interest regarding this work. The research was conducted without personal financial benefit from any third party funding body, nor did any such body influence the execution of the work.

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