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One- and two-slit experiments using photons and electrons: A proper resolution

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ABSTRACT

We construct proper microscopic propositions to consistently capture and explain the interference patterns obtained for electrons and photons, detected individually or otherwise, in one- and two-slit experiments. We propose that for single-photon detections (after time integration), no interference pattern is obtained if one uses non-transparent slit material with slit holes (not diffraction slits). The non-transparent slit material does not permit photons to transmit, reflect internally nor refract. However, the same slit holes can produce the usual interference pattern with electromagnetic waves due to interfering in-phase and out-of-phase light waves. As for the electrons, detected individually or not, partial interference patterns can always be obtained from the two-slit experiment when one of the slits is closed (one at a time), which then can be manually overlapped to produce the complete interference pattern of a double-slit experiment. These new theoretically constructed experimental results for photons and electrons can be readily verified with our current technology using suitable optically non-transparent (for photons) and highly insulating (for electrons) slit materials.

1. Introduction

In this work, our primary objective is to prove that the only way to settle the double-slit experimental results for both photons and electrons (detected individually or otherwise) is by implementing new experimental conditions on slit-material (optically transparent or not for photons and electrically insulating or not for electrons) and slit-type (diffraction slits or slit holes). To support these conditions, we have constructed propositions and quantitative analysis to capture both many-particle (from light waves and electron beams) and accumulated individual detections (from single electrons and single photons) consistently. New experimental observations are also justified and deduced from the said propositions and analysis by changing the slit-material and slit-type in the double-slit experiment. We also show with quantitative analysis that it is not possible to prove the uniqueness of these differing mechanisms to produce the new interference patterns (for electrons and photons) with constructed equations nor calculations. We require experiments to be conducted to confirm whether our theoretically justified experimental results are false or true.

The core mystery of quantum mechanics (wave–particle duality) can be nicely and properly captured by the two-slit experiment (Feynman et al., 1965). In particular, an electron or a photon is both particle- and wave-like, which has been experimentally observed using the one- and two-slit-type experiments by Taylor (1909), the first Young's experiment using weak light source with few photons, Möllenstedt and Möllenstedt and Düker (1955), the first electron diffraction measurement, Jönsson (1961), the first electron diffraction for up to five slits, Merli et al. (1976), the first single-electron interference pattern and recently Bach et al. (2013), one- and two-slit single-electron diffraction, Frabboni et al. (2008, 2011) and Halder et al. (2020). However, the two-slit experiment or any variants of it does not give out the necessary clues to understand why and how an electron behaves like a particle, and a wave, regardless of whether the electron is measured one-at-a-time or all-at-once, or if the electron is measured near the slit or on the screen away from the slit. Therefore, it remains a mystery. Detecting light or photons on the screen away from the slit means that the screen is placed at a distance, D, much larger than the separation between the slits such that the interference pattern is clearly observable.

Any interpretation presented on this wave–particle duality thus far remains a mystery because photons (a quantum particle with mass $m_{\rm ph} = 0$ and charge $q = 0$) should not behave like a wave by producing interference pattern in a two-slit experiment (Feynman et al., 1965). Moreover, electrons passing through the slits (even when released one-at-a-time) generate the interference pattern such that each electron ($m_{\rm e} \neq 0$, $q = -e$) is also detected as a particle on the screen away from the slit (Jönsson, 1961; Bach et al., 2013). Here, we construct the proper and consistent propositions for photons and electrons within the one- and two-slit experiments without violating the well-established

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rules of quantum theory. Subsequently, we exploit these propositions to consistently explain the fringes in the above experiments for electrons and photons. Our propositions constructed herein are microscopically well-defined, and are based on quantum theory. The propositions constructed herein rely on physico-logical analysis. What this means is that our physical mechanisms are constructed on the basis of physical and logical arguments. We then provide consistent quantitative analysis for the constructed physical mechanisms. We shall first focus on the underlying physical mechanisms that are responsible for the formation of interference patterns for both single- and multi-particle detections.

Here, we reconstruct the two-slit interference patterns produced by photons and electrons from scratch. Our primary aims are to provide the propositions and the supporting quantitative analysis to explain the interference patterns produced by individual detections, without violating the standard interference patterns obtained with electromagnetic waves as well as for single-photon (Aspden et al., 2016) and single-electron detections (Bach et al., 2013). We shall also expose the direct role played by the slit materials and slit types (slit-hole or diffraction-slit). Note this, the spin of a quantum particle is assumed to be irrelevant here because the spin (no matter how they interact) cannot switch-on or -off the fringes. In particular, interference fringes can be obtained for both unpolarized or polarized light (spin-one particles) and also for an electron beam (spin-half particles).

It should be straightforward to realize that the interpretation of the experimental results are the ones that are claimed to be false here, not the experimental results. For example, none of these previous interpretations (Aspden et al., 2016; Sawant et al., 2014; Sinha et al., 2010; Raedt et al., 2012; Rengaraj et al., 2018; Magana-Loaiza et al., 2016; Kenmoku and Kume, 2011) (see below) have predicted new observations or changes to the interference pattern with single photons, single electrons, electron beam nor with electromagnetic waves. Even the interaction between quantum particles (electrons or photons) and slits (diffraction slits or slit holes and transparent or non-transparent slit materials) were never discussed or even taken into consideration in any of the previous interpretation (Aspden et al., 2016; Sawant et al., 2014; Sinha et al., 2010; Raedt et al., 2012; Rengaraj et al., 2018; Magana-Loaiza et al., 2016).

In particular, we can recall the most recent interference-calculation made by Sawant et al. (2014) based on the Feynman's path integral formalism. By assuming the existence of many simultaneous paths for a single particle, they have claimed that there exist non-classical paths, which invalidate the superposition of the wavefunctions, and therefore, these paths contribute to the formation of interference pattern for both electrons and photons. As anticipated, the particle nature of electrons (or photons) in their calculations is ignored by employing Fresnel's theory of diffraction. In addition, the assumption that permits one of the particle's possible path to cross the slit plane more than once is also considered as valid despite the fact that a particle cannot change its possible paths by making turns or U-turns on its own.

For example, the said Feynman paths that allow electrons to make turns and U-turns on their own are the ones that are physically unacceptable. In particular, in the Feynman's path integral formulation, one cannot tell whether an electron has taken a particular path because all Feynman paths give the nonzero summed probability amplitudes for each point in spacetime. In other words, all Feynman paths are equally important such that each electron takes all of these Feynman paths simultaneously. Since this is the case studied in Sawant et al. (2014), then why should the first electron's possible paths be any different from the possible paths of the second electron? This means that we need to adjust the Feynman probability amplitudes in an ad hoc manner for each electron such that the electron can be made to make U-turn and/or S-turn on its own, and has the ability to pass through both slits simultaneously. The above argument does not mean the path integral formulation or the quantum mechanics is false.

The physically unacceptable part here refers specifically to the fact that the Feynman's probability amplitudes completely ignore the interaction between the electrons (or the photons) and the slits (slit types and slit materials). This ignorance that is also assumed (Sawant et al., 2014) can be traced back to Feynman et al. (1965). This is why we need to construct physically-valid propositions as we did here, instead of guessing and adjusting the Feynman amplitudes (that also allow all kinds of turns) so as to reproduce the standard observed interference patterns. Note this, no new changes to the interference patterns (between photons and electrons) were calculated from Feynman path integrals. In contrast, we deduce new observations (from the constructed propositions) that quantitatively differentiate the interference patterns (from our calculations) between photons and electrons when they are detected individually.

Here, we have raised the physical and technical problems in Sawant et al. (2014), particularly, with respect to the double-slit experiment using photons and electrons detected individually (see below for more details). There is nothing new in Sawant et al. (2014) because the interference pattern is obtained from pure waves, and these pure waves are falsely represented as particles with an ability to change directions on their own. Pure-wave solutions have been correctly studied and evaluated, which are standard textbook material (Halliday and Resnick, 1988). The above-said problems cannot be settled with mathematics alone because correct physics requires mathematics that includes correct physics in the first place. Without this inclusion, no amount of mathematics, computations, and machine-learning (including Artificial Intelligence, AI) can give us the correct physical mechanisms.

The only way to settle the said problems once and for all is not with endless arguments either, but to run the experiment as proposed here, and not by repeating the standard experiments with standard conditions because these standard conditions contradict with the assumptions made in the calculations (Sawant et al. (2014)) (see below for details). If Feynman paths are to be considered viable, then the standard interference pattern should remain the same for both photons and electrons detected individually (after the required changes made to the slit-type and slit material). Otherwise, it is about time to move away from the Feynman paths.

The inconsistent part (or one of the problems pointed out above) is associated to the incompatibility between Fresnel's diffraction theory and individual particle detection. In particular, the non-classical possible paths for the first particle should be different compared to the second particle, and so forth in single-particle diffraction, which is not discussed based on these possible paths. This is indeed the case as reported in Sinha et al. (2010), Raedt et al. (2012) and Rengaraj et al. (2018) where the Maxwell equations and plane waves were used to reproduce the interference pattern by ignoring the fact that such waves do not represent individual photons. In addition, Magana-Loaiza et al. (2016) have also exploited the plane wave subject to Helmholtz equation, which again, does not and cannot represent individual photons. Therefore, the work of Sawant et al. (2014), Sinha et al. (2010), Raedt et al. (2012), Rengaraj et al. (2018) and Magana-Loaiza et al. (2016) implicitly pin point why we need to first construct the proper physical mechanisms in order to explain the formation of fringes.

Further support can be obtained from the calculations carried out by Kenmoku and Kume (2011), which rely on the superposition of quantum scalar fields such that these fields are treated as two spherical waves that has been represented as state vectors, namely, $\langle A|$ and $\langle B|$ (from two sources representing two slits) and these states obey $\langle A|B\rangle \neq 0$. This means that, the two spherical states are not independent (in this case, the states are not orthogonal), or they are said to be in a superposition such that these non-orthogonal states can produce interference pattern. Even though adopting the quantum scalar fields is a correct step to reproduce the Young's double slit interference pattern, but their approach is not suitable to find the physical mechanisms, and it is also not appropriate to evaluate single quantum particle detection.

For example, superposition always requires this condition $\langle A| \neq 0 \neq \langle B|$ to be valid, which explains why Kenmoku and Kume's objective was never about calculating the single-particle interference pattern produced after time-integration (Kenmoku and Kume, 2011). Even if it is quantum mechanically legal to assume that a single quantum particle with its quantum scalar field can be in a superposition such that $\langle A| \neq 0 \neq \langle B|$ and $\langle A|B\rangle \neq 0$, but this does not uniquely explain or even describe the role of slits because (based on this superposition idea) even a single slit should be able to produce the Young's interference pattern. This implies that the particle knew *a priori* when to be in superposition (when there are two slits), and when not to be (when there is only one slit), which leads us back to square one.

The above inconsistencies (due to nonclassical paths and superposition) are well-known that had stayed unresolved since the early days of quantum mechanics. We shall tackle these issues unequivocally and point out the origin for the false misconception with our constructed propositions. The primary motivation for this work originates from the fact that Feynman falsely assumed that the two-slit experiment for photons are based on two 'punched slit-like holes' (or two openings) (Feynman et al., 1965) where Feynman did not discuss nor point out the possible interaction(s) between a quantum particle (from the source) and the slit. In one- or two-slit experiments for photons however, this is not the case because the interference (or diffraction) pattern obtained and reported in the scientific literature and textbooks for photons thus far specifically made use of diffraction grating containing one or two slits without any holes or actual openings. This is the original motivation for the propositions presented here.

The calculations reported in Sawant et al. (2014), Sinha et al. (2010), Raedt et al. (2012) and Magana-Loaiza et al. (2016) also assumed the two slits as two punched slit-like holes (slit-holes) for photons, and therefore, their calculations is not relevant for the fringes obtained in actual experiments with diffraction slits. In particular, the calculations are carried out for slit-holes, but the performed experiments made use of diffraction slits (Sawant et al., 2014; Sinha et al., 2010; Raedt et al., 2012; Magana-Loaiza et al., 2016), or the experiments made use of slit-holes and electromagnetic waves, but the conclusion is for individual photon's looped trajectories (Rengaraj et al., 2018). Therefore, their calculations (Sawant et al., 2014; Sinha et al., 2010; Raedt et al., 2012; Magana-Loaiza et al., 2016) have got nothing to do with their own experimental results. It is worth noting that, Magana-Loaiza et al. (2016) calculated the interference pattern by activating the interaction between plasmons on the metallic slit-holes and that of the source electromagnetic wave representing photons wavefunction by adjusting the probability terms. Strangely, the stated interaction and its changing strength was interpreted as the proof for the existence of looped trajectories. In fact, for materials with diffraction slits and for the experimental set-up depicted in Magana-Loaiza et al. (2016), the said interaction also gives rise to refraction due to dispersion, Raman scattering (Raman, 1928) and Compton effect (Compton, 1923) when the incident photons pass through a prism or oil/Au/glass system, which was ignored in Magana-Loaiza et al. (2016).

Therefore, physically, we cannot accept the interpretation that requires looped trajectories because when we replace the slits made of gold (used in Magana-Loaiza et al. (2016)) with a highly insulating material (that does not interact quantum mechanically with photons), we would not be able to observe the so-called looped-trajectory effect for photons detected individually. This means that the photon(source)-electron(from the slit) interaction is the cause for the changing interference pattern in all directions (x, y, z). Hence, loop trajectories cannot be an intrinsic property of any quantum particle or electromagnetic wave, and the interference pattern is produced due to the interaction just stated above. We shall discuss this interaction in Propositions 2P and 7E in more detail, which have been proposed much earlier in 2014 (Arulsamy, 2014).

We shall expose the direct role played by the slit materials and slit types (slit-hole or diffraction-slit) that are often ignored and confused, for example, see (Sawant et al., 2014; Sinha et al., 2010; Raedt et al., 2012; Magana-Loaiza et al., 2016). This confusion is a fact. In particular, Aspden et al. (2016) simply stated that the slits were diffraction slits without saying the slits are not slit holes, and the slit material is transparent to photons or light. The importance of noting this missing detail is that when one uses diffraction slits (not slit holes) made from optically transparent material that permits single photons and/or light to reflect and refract internally, then the question, 'which slit?' is ambiguous, if not meaningless.

To have an idea about the new physics presented in this article, we briefly elaborate the results obtained by Aspden et al. (2016). Even though Aspden et al. (2016) used the diffraction slits (made from the materials that allow photons to transmit, reflect internally and refract) for single photon detection, but we also need to experiment with different slit materials. For example, the diffraction slits need to be replaced with slit holes (made from the materials that do not permit photons to transmit, reflect internally or refract). This is to check whether there is any difference in the interference pattern between the two different slit materials and slit types, which have been ignored thus far. We identify and address this difference unambiguously with our newly constructed propositions, which can be readily tested with experiments. However, we stress that the said difference was actually first hinted in Merli et al. (1976) and Rosa (2012) much earlier where the hint reads—photons or electrons will have to interact with the slits to produce the interference pattern. This should not be surprising because we always need slits (diffraction slits or slit holes) to produce interference patterns. Therefore, we cannot solely rely on the properties of photons and electrons or the properties of the field such as the electromagnetic field for photons, or electric (and/or magnetic) field from the moving electrons to construct the mechanisms responsible for the observed interference patterns.

The formalism based on wave function is not adopted here simply because the wave function is a guessed function and therefore, the deduced physics are also guessed and thus ambiguous. Secondly, the wave function collapse notion has remained an assumption with no proper physical mechanism attached to it and there is no proper experimental support for the said collapse. Thirdly, the wave function formalism does not give any new experimental predictions on the formation of interference pattern. The above reasons expose why our technical arguments are new and unique because the physical mechanisms highlighted here provide new experimental predictions. Apart from that, the presented arguments, propositions and quantitative analysis do not violate the known physics of the standard interference patterns.

2. Propositions

We now state (without any supporting arguments) all the relevant propositions for photons and electrons required to understand the formation of interference pattern within the new one- and two-slit experimental set-ups. The proposals are also valid for individual particle detections. We shall provide the physical arguments in support of the propositions in the section after this, and prior to conclusions, we shall elaborate on the new experimental set-ups for the proposed new observations as well as quantitative analysis for all our propositions.

2.1. Propositions for individual photons and light

Proposition 1P. *The massless and chargeless photons do not interact with each other, however, one waving group of photons can interfere (destructively or constructively) with another waving group of photons (after exiting the slits) to produce interference pattern. Here, this waving groups of photons are nothing but the electromagnetic wave or light.*

Note: The properties of light (electromagnetic waves) are not included in this proposition because it is well defined based on wave equation. In this proposition, we do not need to invoke the notion that a photon interferes with itself as proposed by Dirac. In particular, each photon interferes with itself is an absurd assumption because the standard 2-slit experiment with photons detected individually invalidates this assumption. For example, a single photon in a single slit experiment detects a single photon on the screen. A single photon in a 2-slit experiment also detects a single photon on the screen. Hence, the assumption that each photon's self-interaction has a role to play to explain the standard interference pattern is already a false assumption to begin with. Apparently, this notion is also irrelevant because the waving property of photons, the slit material and the slit type are the ones that decide whether interference pattern can be observed or not. The collective waving property of photons (or a group of waving photons) should define the electromagnetic waves. It is unfortunate that we cannot define any given individual photon in any 'deeper' sense than this.

Proposition 2P. *The new experimental set-up and the photon energy is chosen in such a way that individual photons do not interact with the electrons at the edges of a slit. The energy of the waving groups of photons should be low enough so as not to interact with electrons from the slit material or the material with embedded slits. This material should never let the photons to pass through (via transmission and/or reflection or by any other process) in regions other than the opening (the slits). If individual photons are allowed to pass through (via reflection and transmission), one-at-a-time, through the slit material between the slits (not through the slit opening), then one should be able to observe the interference pattern from the time-integrated intensity. This proposition strictly denies the notion that any one photon has the supernatural ability to pass through both slits (in a two-slit experiment) simultaneously to produce interference pattern.*

Proposition 3P. *Two photons, or two groups of waving photons can never be exactly identical because they are produced by microscopically interacting physical processes. Any interacting physical process, when evaluated microscopically, can never be made exactly identical in every aspect, and even in this case, photons always obey the Heisenberg's uncertainty principle. If the two photons or two groups of waving photons have the same energy and the same Pancharatnam phase (Arulsamy, 2020), then they have got to be exactly the same. However, the Heisenberg's uncertainty principle is valid for photons regardless of whether a photon's energy and Pancharatnam phase are identical or not, with another photon.*

Proposition 4P. *Waving groups of photons, p1 that enters s1 only without interacting with s2 (even if it is opened) do not generate any interference pattern because* $I_{p1} \longrightarrow (I_{p'},I_{p''},I_{p'''})_{s1} \neq 0$ *and* $I_{p1} \longrightarrow (I_{p'},I_{p''},I_{p'''})_{s2} = 0$. *If* $p_{new}1$ *is composed of p1 and p2, then* $p_{new}1$ *can interact with both s1 and s2 to give* $p_{new}1 \longrightarrow (p',p'',p''')_{s1} * (p',p'',p''')_{s2}$ *such that* $I_{p_{new}1} \longrightarrow (I_{p'},I_{p''},I_{p'''})_{s1} * (I_{p'},I_{p''},I_{p'''})_{s2}$. *Here,* $*$ *denotes* $(p',p'',p''')_{s1}$ *interferes constructively (in-phase) and destructively (out-of-phase) with* $(p',p'',p''')_{s2}$. *Here, p1 and p2 denote the waving groups of photons before entering the slits, the labels, s1 and s2 refer to the slit-1 and slit-2, respectively,* p', p'' *and* p''' *are the waving groups of photons after passing through or after interacting with s1 or s2. In addition,* I_{p1} *is the intensity of the waving groups of photons prior to entering any of the slit, while,* $I_{p'}$, $I_{p''}$ *and* $I_{p'''}$ *are the possible intensities of the waving groups of photons after passing through or interacting with a particular slit (s1 or s2). Obviously,* p', p'' *and* p''' *are possible groups of photons exiting the slit such that only one of the groups of waving photons, namely,* p', p'' *or* p''' *is formed at a given time, regardless of whether the experiment is for a single photon or for groups of photons. Therefore it is technically incorrect to treat* p', p'' *or* p''' *with a single wave function due to the different probability to form* p', p'' *or* p'''.

The above waving property (for groups of photons or for a single photon) obey Maxwell equations. There is no such thing as single photons do not wave, while only light (that is composed of groups of photons) has a wave property. This means that, the waving property for photons is due to waving photons or a waving single-photon, which gives meaning to the notion of frequency of light. The photon itself is a waving entity with proper frequency subject to Maxwell's equation. In other words, the above definition of waving groups of photons (or a waving single-photon) supports the fact that the energy of photons (or a single-photon) comes from this waving property, and the energy is entirely kinetic in nature. This waving property also implies that even a waving single-photon is not a point-like particle. On the other hand, the electrons are not point-like particles not because we have to represent them with wave functions subject to the Schrödinger equation, but because each electron's wave-like property is confined by the charge and mass distribution of the electron. Therefore, the electron's wave function is not and cannot be subject to Maxwell's wave equation. This means that, there is no such thing as waving electrons like the waving photons defined above for photons. Hence, the total energy of an electron is composed of kinetic and potential (due to its charge and mass) energies. These unique definitions (for photons and electrons) support the fact that the photons have got to be massless, while electrons should be massive.

2.2. Propositions for individual electrons and electron beam

Proposition 5E. *Individual electrons or an electron beam do interact with each other and also with other electrons in material with embedded slits. This material should never let the electrons to pass through (via tunneling or conduction or by any other process) in regions other than the opening (the slits).*

Proposition 6E. *Two or more electrons from the source, after passing through the slits s1 (one-half of the electrons) and s2 (the other half), do interact with each other prior to detection by* s'''. *But such interaction is not the cause for the interference pattern depicted in Fig. 2(c). Here,* s''' *is the screen at an appropriate distance from the slits, s1 and s2, whereas,* s' *and* s'' *refer to the screens that are placed just before the slits and just after the slits, respectively. The interaction between electrons in an electron beam is a function of* x *(the distance from the source to the slit and from the slit to the screen) as it should. It is a function of* x *with different interaction strengths before and after exiting the slit. Nevertheless, the said electron–electron interaction does not and cannot cause interference patterns. The interference patterns are actually caused by the interaction between the electrons from the source (electron beam) and the electrons from the slit material.*

Proposition 7E. *The electron wavefunction transformation is due to electron(from the source)-electron(from the material with embedded slits) interaction, which is asymmetric because s2 still exists, even though it is blocked. This asymmetric effect will be stronger if there is any potential difference between the slit material and source or between the source and the screens. For example, the electric field distribution near the slits will be asymmetric (if s2 is blocked). Therefore, the electrons are assumed to have the following transformation probabilities,* $qp1 \longrightarrow p'' > qp1 \longrightarrow p''' > qp1 \longrightarrow p'$ *(see Fig. 2(a)). If there is only one slit (s2 is not blocked, but does not exist) as sketched in Fig. 2(b), then the transformation probabilities is given by* $qp1 \longrightarrow p'' > qp1 \longrightarrow p''' = qp1 \longrightarrow p'$. *Note this, each electron is denoted by qp such that for two electrons, we denote them as qp1 and qp2, respectively, and so on for more electrons.*

Proposition 8E. *On the basis of Proposition 7E, the overlapping of intensity peaks from s1 (with s2 closed) and s2 (with s1 closed) can generate the interference pattern observed with both s1 and s2 opened. In particular, we strictly require,*

$$(I_{p'},I_{p''},I_{p'''})_{s1} \circ (I_{p'},I_{p''},I_{p'''})_{s2} = (I_{p'},I_{p''},I_{p'''})_{s1} \oplus (I_{p'},I_{p''},I_{p'''})_{s2}, \tag{1}$$

where $\oplus$ *denotes the total accumulation of detected electrons on* s''' *due to both s1 and s2 opened. Here, the intensities in Eq. (1) refer to electrons or produced by electrons (an electron beam or accumulated electrons, if detected individually). Recall that* $I_{qp1} \longrightarrow (I_{p'},I_{p''},I_{p'''})_{s2}$ *where* I_{qp1} *is the intensity of the electron prior to entering any of the slit, while,* $I_{p'}$, $I_{p''}$ *and* $I_{p'''}$ *are the possible intensities of the electron after passing through a particular slit (s1 or s2).*

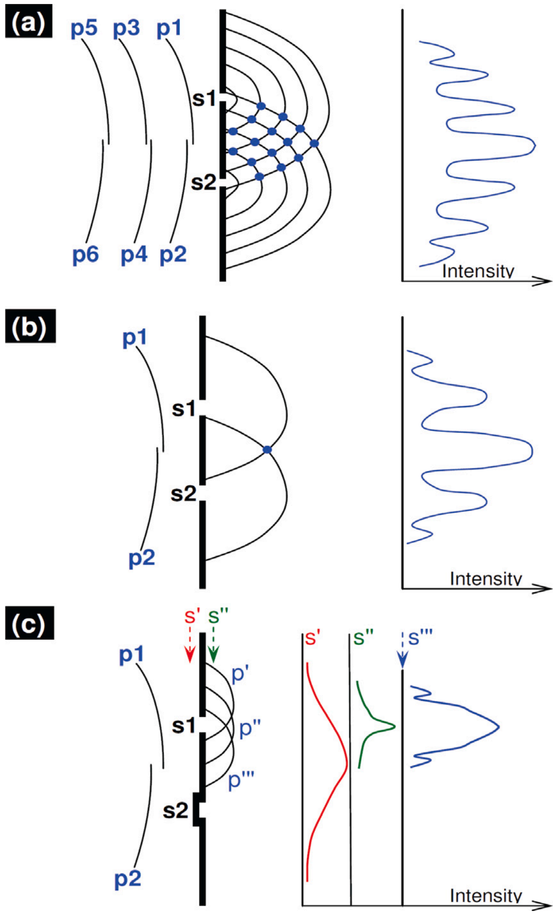

Fig. 1. (a), (b) and (c) depict the two-slit experiments for photons or light. (a) p1, p2, ⋯, p6 denote six groups of waving photons approaching slits, s1 and s2. The dots (after the slit) in (a) represent the points where constructive interference occur. (b): Interference pattern for two groups of waving photons approaching the slits simultaneously. (c): One-photon-at-a-time intensity pattern with s2 closed (after time integration). In (c) s′, s″ and s‴ denote the screens (follow the appropriate arrows) that detect the groups of waving photons, placed just before the slits (s′), just after the slits (s″), and at a distance, D, which is much greater than the separation between the slits (s‴). Here, p′, p″ and p‴ each represents one waving group of photons after interacting with the slit.

3. Physical mechanisms and experimental predictions

3.1. One- and two-slit experiments using photons or light

Let us first re-construct the standard two-slit experiment and its interpretation for photons (light) as depicted in Fig. 1(a), (b) and (c). The probability for multiple photons to enter or diffracted by both slits simultaneously is maximum for light, hence we can suppose p1 and p2, p3 and p4, and p5 and p6 are groups of waving photons in pairs entering slits, s1 and s2 such that p1 and p2, and so on enter their respective slits simultaneously. These groups of waving photons (not an individual photon) can behave like a 'proper wave' ($p = h/\lambda$; de Broglie formula), and therefore, one obtains the interference pattern sketched on the screen (see Fig. 1(a)). This pattern (due to photons) originated from the constructive (in-phase) and destructive (out-of-phase) interference. The constructive interference is indicated with solid circles (•) between the slits and the screen, which occur if two groups of waving photons are in phase (see Fig. 1(a)).

However, if p(1,3,5) and p(2,4,6) are pairs of individual photons (six photons, instead of six groups of waving photons), then interference pattern will not be observed because photons do not interact with each other to generate constructive or destructive interference. As such, interference pattern depicted in Fig. 1(a) is produced by two groups of waving photons (p1 and p2, p3 and p4, and p5 and p6 and so on) that give rise to constructive and destructive interference. Here, p1 denotes one group of waving photons, and so on. The sketched interference patterns in all figures reported here are not to scale, for example, some of their peak-intensities are exaggerated for visual effect. Based on the above arguments, we can construct the first two propositions, namely, Propositions 1P and 2P.

Before we proceed further, let us first point out that our waving-group-of-photons assumption is physically acceptable. let us elaborate the above propositions (Propositions 1P and 2P), which are unique for photons compared to electrons. In particular, massless photons cannot obey the Schrödinger equation,

$$-\frac{\hbar^2}{2m_e}\frac{d^2\Psi(x)}{dx^2} + V(x)\Psi(x) = E\Psi(x), \tag{2}$$

which is for massive and charged electrons because $m_e \neq 0$ where $\hbar$ is the Planck constant divided by 2π, E is the energy eigenvalue, $\Psi(x)$ is the wavefunction, and $V(x)$ is the potential that bounds the electrons. Instead, we should be using the proper Maxwell's 'wave equation',

$$\frac{\partial^2\mathbf{E}}{\partial t^2} = c^2\frac{\partial^2\mathbf{E}}{\partial x^2}, \tag{3}$$

for photons where c is the speed of light and $\mathbf{E} = E_0\sin(kx - \omega t)$, which is the electric field component of the electromagnetic wave. These equations are one-dimensional, and are sufficient for our purposes. Apparently, electrons do not obey the Maxwell's wave equation. Now, if we define $\Psi(x)$ as a plane wave (from Eq. (2)),

$$\Psi(x) = A(x)\exp\left[i\phi(x)\right], \tag{4}$$

which is a proper wave anyway, then both light (that satisfies Eq. (3)) and electron beam (that satisfies Eq. (2) with a range of energies and speeds and a wave packet property) can be regarded as proper waves, and therefore, they shall always produce the fringes in any two- or multiple-slit experiments (due to constructive and destructive interference), provided that the screen (or detector) is placed at s‴. A proper wave here satisfies Eq. (3) (for light) and Eq. (2) (for a free electron beam) such that the photon's or the electron's position is infinitely undefined. Here, a wavefunction that represents an electron from an electron beam cannot satisfy Eq. (3) nor Eq. (4) because $m_e \neq 0$ and $q = -e$.

Even the paraxial equation that is usually exploited to study laser beams cannot be made to satisfy the Schrödinger equation (Verdeyen, 1981). Here, $A(x)$ and $\phi(x)$ denote the amplitude and phase, respectively. However, unlike light, an electron beam is not an electromagnetic wave, which means, by definition, photons and electrons are different types of particles, and should be treated as such. Even though this difference is not responsible for the appearance and disappearance of fringes, but it determines the different physical mechanisms required by photons and electrons to produce their respective interference patterns. Our propositions claim that this difference is intrinsic due to Eqs. (2) and (3), which is valid for both single-particle and many-particle diffractions. However, the said difference has been anticipated much earlier by comparing the many-photon interference pattern obtained from the Young's experiment (constructive and destructive interference are responsible for the fringes using light (Suppes and de Barros, 1994)) and the single electrons experiment performed in Merli et al. (1976) as pointed out by Rosa (2012). Merli et al. (1976) were the first to claim (based on their single-electron measurements) that each electron interacts within the apparatus to produce the fringes after time integration.

The problem here is that electrons or photons are not entirely waves in a real physical sense, meaning, these photons and electrons satisfy the wave–particle duality, which cannot be correctly represented by pure waves as required by Eq. (3) for photons, or by Eq. (4) for electrons. For example, neither Eqs. (3) and (4) can be used to explain the formation of interference pattern produced when the photons or electrons are detected one-at-a-time on s‴. Thus, we have no other choice but to properly construct the relevant postulates from scratch such that, these postulates could be used to explain both situations consistently; for many photons and electrons, as well as for photons and electrons released one-at-a-time. As a matter of fact, these two contradicting situations are the ones responsible for the mystery of quantum mechanics as pointed out by Feynman.

In other words, our objective stated in the abstract can be readily met if and only if we could come up with proper propositions to address these observations; (a) the intensity in one-slit type experiments, (b) the fringes in two-slit experiments using light and an electron beam, (c) the time-integrated intensity obtained from the two-slit type experiments using photons and electrons released one-at-a-time. As for the question, 'which slit?', one can only obtain such information from s″ (there is no other way because we have to detect the particles at the slits). The detection on s″ means that some photons do pass through a particular slit, and some through the slit material (as postulated in Proposition 2P) to produce the interference pattern.

It is unfortunate that we cannot detect the same particle twice (on s″ and again on s‴). Moreover, in all our analysis presented here, we will not invoke the concepts of superposition, localization and delocalization (explicitly nor implicitly) to address the formation of interference pattern. For example, when we consider an electron as a particle, it does not imply that the electron now is a localized entity. In fact, we will not use these three terms or concepts anywhere in our analysis. In Fig. 1(b), we only allow two groups of waving photons, p1 and p2 to pass through the slits s1 and s2, respectively, followed by p3 and p4, and so on. Having said that, we can now construct Proposition 3P.

Similar to the set-up depicted in Fig. 1(b), if we now close s2 as shown in Fig. 1(c), one can then observe the intensity peaks without interference as sketched on screen s‴. Therefore, the pattern on s‴ (see Fig. 1(c)) differs from Fig. 1(a) and (b) as it should be. Moreover, note the additional weak intensity peaks at the edge on s‴ (Fig. 1(c)) due to the above stated differences or fluctuation (indicated with p′, p″ and p‴). For example, each time p1 passes through s1, p1 transforms into one of these three extreme cases (possible waving group of photons), p′ or p″ or p‴ where $p1 \neq p' \neq p'' \neq p'''$, and $p1 \longrightarrow p''$ is assumed to have the highest intensity, while $p1 \longrightarrow p'$ and $p1 \longrightarrow p'''$ are assumed to have identical intensities, but much lower than $p1 \longrightarrow p''$. These different intensities arise from different transformation probabilities, in particular, $p1 \longrightarrow p''$ has the highest probability, while $p1 \longrightarrow p'$ and $p1 \longrightarrow p'''$ are equally probable, but much smaller (because the above stated fluctuation is smaller) than $p1 \longrightarrow p''$. For the different-intensity assumptions to be valid, we also require this condition—the photons are not to be perturbed between the source and the slits such that the intensity peak is as depicted on s′ (see Fig. 1(c)).

Apart from that, if we place additional screens s′ and s″ near the slits, one is just before the slits, and the other just after the slits, then the expected peak in each case are also sketched in Fig. 1(c)—follow the arrows, s′ and s″. Obviously, the fluctuation is negligible to be significantly detected on s″ because the screen is too close to the slits, while s′ does not record the stated fluctuation because such fluctuation does not exist for the photons have not entered s1. Here, s′ detects both p1 and p2. With this additional information, we can write down our final proposition for photons (detected individually or otherwise), Proposition 4P.

Now, by referring to Proposition 4P, it is easy to note that it satisfies Young and Taylor (1909) double-slit experiments. The interaction between an electron and the slit does not have to be a 'mechanical' type as proven in Merli et al. (1976). Here and elsewhere, the phrase 'interact mechanically' means it is induced by Coulomb interaction or negligible photon(source)-electron(slit) interaction such that the quantum mechanical part of the interaction is fortunately not needed (for Coulomb-like electrostatic interaction) or negligible (for photon(source)-electron(slit) interaction). The said interactions (the photons with the slit, and the electron–electron) are respectively responsible for the probability transformation (for photons) and wavefunction transformation (for electrons).

In summary, the intensity peaks on s′ and s″ should be identical if we add those screens in the experimental set-up shown in Fig. 1(a) and (b). However, instead of one peak, there should be two identical peaks on s″ in Fig. 1(a) and (b) because both s1 and s2 are open (we did not show this for it is obvious). In addition, the interference pattern will not be observed whether one or many waving group(s) of photons are allowed to pass through s1 only (with s2 closed) because each waving group of photons that enter s1 does not interact with s2. Even if they do interact, for example if we have $p_{new}1$ instead of p1, the interference pattern still will not be observed because s2 is closed. In this case, even if $p_{new}1$ had interacted with s2, the intensity peak(s) are still entirely determined by s1 alone because s2 is closed.

The relevant interaction here is between a waving group of photons (p1) and s1 (or both s1 and s2), which is not identical to the interaction between another waving group of photons (p2) and s1 (or both s1 and s2). Hence, this interaction is also responsible for the fluctuation (p′, p″ and p‴) stated earlier. The interference pattern observed on s‴ is entirely due to interaction between two waving groups of photons, $(p',p'',p''')_{s1}$ and $(p',p'',p''')_{s2}$. Recall that p′ or p″ or p‴ is a group of photons that have passed through the slit such that $p1 \longrightarrow (p',p'',p''')$. Therefore, the overlapping of intensity peaks from s1 (with s2 closed) and s2 (with s1 closed) cannot generate the interference pattern observed with both s1 and s2 opened. In other words,

$$(I_{p'}, I_{p''}, I_{p'''})_{s1} \circ (I_{p'}, I_{p''}, I_{p'''})_{s2} \neq (I_{p'}, I_{p''}, I_{p'''})_{s1} * (I_{p'}, I_{p''}, I_{p'''})_{s2}. \quad (5)$$

Apparently, $\circ$ denotes the overlapping of $(I_{p'},I_{p''},I_{p'''})_{s1}$ with $(I_{p'},I_{p''},I_{p'''})_{s2}$.

3.2. One- and two-slit experiments using electrons

We now repeat the experimental set-up given in Fig. 1(c) with electrons sent one-at-a-time onto the screen s′ or s″ or s‴ where each case is treated separately (see Fig. 2(a)). Note that slit s2 exists but blocked in Fig. 2(a), while in Fig. 2(b), s2 does not exist, and we shall discuss this difference shortly. Anyway, unlike photons that need to be defined as waving groups of photons, electrons on the other hand, cannot be treated as such because $m_e \neq 0$ and $q = -e$. Consequently, each electron needs to be defined as individual quantum particle (qp), that can only be represented by an appropriate wavefunction, and electrons cannot form any waving groups of electrons due to repulsive interaction between them, and with other quantum matter (the material with embedded slits). Earlier, the material with embedded slits, and the photon energy are so chosen to avoid significant interaction between individual photons and the electrons from the material with embedded slits such that the waving group of photons (not individual photons) interact with the slits edges (not with the electrons). For an obvious reason (stated above), we cannot satisfy this requirement properly for electrons. Indeed, electrons and photons are two different types of quantum particles. Hence, we can now construct Propositions 5E and 6E. By sending one electron at-a-time through a single slit set-up (the second slit is blocked: see Fig. 2(a)), and after sufficient number of electrons detected, one obtains the pattern shown on s‴, which is different from Fig. 1(c). However, the intensity peaks on s′ and s″ remain the same for both photons and electrons as it should be. Earlier, we have proposed that one needs two waving groups of photons (p1 and p2) or one waving group of photons ($p_{new}1$) to pass through both slits in order to produce the required fringes. On the contrary, the mechanism for electrons to produce such fringes is due to electron(from the source)-electron(from the material with embedded slits) interaction. This interaction is different if the material has only one slit (not one

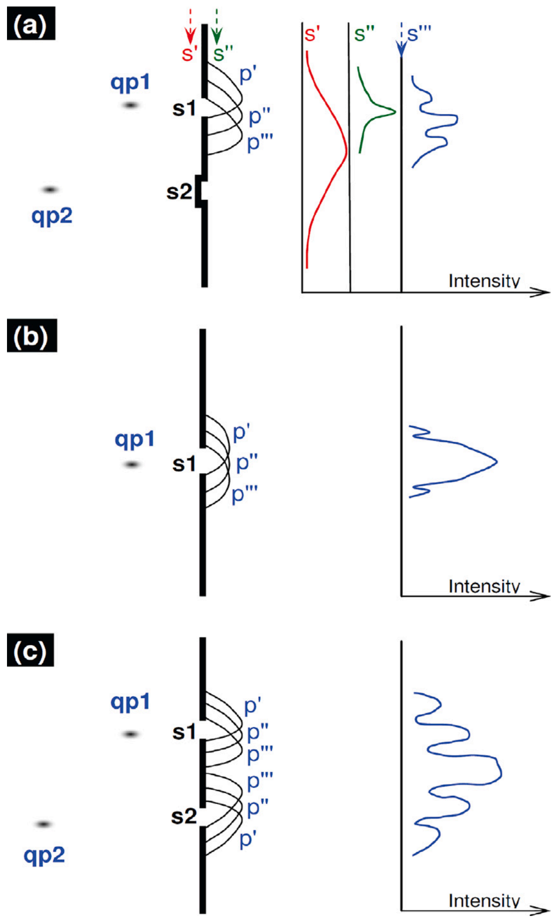

Fig. 2. (a), (b) and (c) depict the one- and two-slit experiments for electrons. (a) qp1 and qp2 are individual electrons approaching slits, s1 and s2 (blocked) one-at-a-time and they produce one-half of the interference pattern (after time integration or after accumulating enough individual electron detections). If we repeat (a) with s1 blocked and s2 opened, one can overlap this result with (a) to produce the complete fringes, identical to the one shown in (c). Here, similar to Fig. 1(c), s′, s″ and s‴ denote the screens (follow the appropriate arrows) (b): The electrons (sent one-at-a-time and after time integration or as an electron beam) do not produce any fringes because s2 does not exist. (c): If the electron sent one-at-a-time (and after time integration) or as a beam, one obtains the full interference pattern (provided s2 is also open). For electrons, p′, p″ and p‴ represent transformed electron wavefunctions after interacting with electrons from the slit-material. Note that s2 is blocked in (a) in such a way that electrons cannot pass through the blocked slit in any way.

slit is open, while the other is blocked). Material with one and two slits give rise to different interaction strengths between electrons from the source and the electrons from slit material. For example, for the case shown in Fig. 2(a), the transformation reads qp1 ⟶ (p′,p″,p‴) where qp1 ≠ p′ ≠ p″ ≠ p‴, which indicate different possible transformations.

Each time an electron (qp) passes through s1 (s2 exists but blocked, see Fig. 2(a)), it interacts with the electrons from the material with two embedded slits, and therefore, gets its wavefunction transformed accordingly (due to its interaction with slit's material in the presence of blocked s2) into one of these three extreme cases (possible wavefunctions), p′ or p″ or p‴ where qp1 ⟶ p″ is again assumed to have the highest probability, followed by qp1 ⟶ p‴, while qp1 ⟶ p′ is the least probable. In other words, electrons entering s1 transform satisfying this inequality, qp1 ⟶ p″ > qp1 ⟶ p‴ > qp1 ⟶ p′. Therefore, we can now construct Proposition 7E.

The potential difference stated in Proposition 7E do exist near the slit region or a biprism to split the electron beam or to divert an electron to the left, or to the right 'opening', as required in Merli et al. (1976). Due to this Coulomb interaction induced mechanical interaction and Proposition 7E, we can construct the final proposition for electrons (detected individually) and for an electron beam, which is given in Proposition 8E.

In summary, comparing Eq. (5) for photons with Eq. (1) for electrons, one can conclude that Eq. (5) negates Eq. (1) (or Eq. (5) = ¬Eq. (1)) due to sign-change from '=' to '≠', and Eq. (5) also counters Eq. (1) (or Eq. (5) = ⊥Eq. (1)) because Eqs. (5) and (1) refer to two different physical mechanisms in order to reproduce the intensity peaks on s′ and s″, and the fringes on s‴. The overlapping of intensity peaks from s1 (s2 does not exist) and s2 (s1 does not exist) do not generate the interference pattern observed with both s1 and s2 opened as depicted in Fig. 2(c) where Eq. (1) reads

$$(\mathrm{I_{p'}}, \mathrm{I_{p''}}, \mathrm{I_{p'''}})_{\mathrm{s1}} \circ (\mathrm{I_{p'}}, \mathrm{I_{p''}}, \mathrm{I_{p'''}})_{\mathrm{s2}} \neq (\mathrm{I_{p'}}, \mathrm{I_{p''}}, \mathrm{I_{p'''}})_{\mathrm{s1}} \oplus (\mathrm{I_{p'}}, \mathrm{I_{p''}}, \mathrm{I_{p'''}})_{\mathrm{s2}}. \tag{6}$$

Here, the experimental set-up shown in Fig. 2(b) gives rise to symmetric interaction between the source electron and the electron from the material with embedded slit. In this case, the electric field distribution near the slit due to potential difference stated above (if it exists) is also symmetric.

4. Additional notes

The propositions given above, especially the one for electrons (charged mass) can be readily exploited to reproduce the interference pattern obtained from neutrons (neutral mass) and molecules (massive and neutral with polarizable outer electrons). In particular, neutrons and molecules also have produced the interference pattern as reported in Zeilinger et al. (1988), Carnal and Mlynek (1991) and Eibenberger et al. (2013). This is not surprising because we can extend the following propositions, 5E, 6E, 7E and 8E to the above massive particles (neutrons and molecules). The extension is straightforward because the Coulomb interaction between an electron(from the source) and the electron(from the material with embedded slits) should be replaced by the 'mechanical' interaction between a neutron(from the source) and the nucleus(from the material with embedded slits).

For the molecules, the interaction is between a molecule(from the source) and an atom or a molecule(from the material with embedded slits). Therefore, the mechanism to produce the interference pattern remains the same for electrons, neutrons and molecules, which are captured by these propositions, 5E, 6E, 7E and 8E. In other words, neutrons and molecules also obey the same physical mechanism (with different interactions) to obtain the interference pattern depicted in Fig. 2. Dipole moments of molecules cannot cause interference patterns. Dipole moments may influence the interaction between molecules from the source, before and after exiting the slits, but the interacting dipole moments do not and cannot cause the formation of interference patterns. To demonstrate the effect of dipole moments causing the interference pattern, one has to produce the said pattern exclusively with the slit material that is composed of dipole moments. Therefore, the interacting dipole moments between molecules (from the source) do not play any role in the formation of interference pattern because the interaction between the molecules outer electrons and the outer electrons from the slit material is entirely responsible for the interference pattern. If the slit material is also composed of dipole moments, apart from its outer electrons, then we need to know whether the effect of the electron(molecule)-electron(slit) interaction is reduced by the dipole moment(molecule)-dipole moment(slit) interaction in order to deduce the quality of the formed interference pattern.

In this work, our focus has been on photons and electrons because once their interference pattern has been made explicit physically and consistently, then it is quite straightforward to apply to other particles, namely, neutrons and molecules. The second reason is that it is far more difficult to handle or evaluate the interference pattern obtained from elementary particles such as photons and electrons consistently.

Ideally, it may seem elegant to unify the analysis by treating the photons and electrons as quantum particles, and then within this analysis, we can set $m = 0$ for photons and $m > 0$ for other massive particles. However, it is impossible to devise a single consistent formalism to deal with such unification in the presence of wave–particle duality so as to evaluate the interference pattern obtained from time-integrated individually-detected quantum particles. For example, the wave–particle duality cannot be defined precisely and uniformly for different types of quantum particles detected individually, which can be anticipated from the fact why we need Eq. (2) for electrons and Eq. (3) for photons. Let alone the complicated (due to wave–particle duality) and specific interactions experienced by different types of quantum particles interacting with the particles in the slit material (or at its edges). Despite this fact, we shall provide quantitative analysis for the photons and electrons without violating quantum mechanics and wave theory in the last section prior to conclusions.

5. Experiments with new proposed observations

To properly verify our propositions, we first have made our arguments to be logically precise with appropriate physical mechanisms that consistently obey quantum mechanics and experimental observations made thus far, as well as predict unique and novel observations. Subsequently, we shall provide the quantitative analysis required to capture individual detections of photons and electrons for all our constructed propositions. The propositions make explicit the differences in the interference pattern produced by photons from that of the electrons in such a way that these propositions can be tested experimentally with new proposed observations. In addition, we have also identified the roles played by the slit-material and slit-type in producing the interference patterns for photons and electrons, respectively. All our unique and newly predicted observations proposed here (see below) are new and detailed enough that can be readily falsified with present-day experiments.

5.1. Experiments for individual photons and for light

It is worth noting here that Aharonov et al. (2017) had exploited the same interaction proposed here (between electrons as source particles with slits), where our proposition is already available since 2014 (Arulsamy, 2014). This proposition is also exposed and discussed again in Arulsamy (2016) by the author of this work much earlier than Aharonov et al. (2017). Apart from that, our propositions constructed herewith are complete because we considered both electrons and photons in a technically consistent manner with respect to their interaction with the material with slit(s).

To prove our propositions, we only need to carry out the one- and two-slit experiments with photons ((a) for light and (b) for photons detected individually). The only required changes to the usual experimental set-up using photons are (c) the type of slit material that should be completely non-transparent, and (d) the slits should be the actual openings (not diffraction grating). With the above changes [(c) and (d)] made to the experimental set-up, the new experimental results for a double-slit cannot produce any interference pattern (on the screen, s‴) for photons detected individually after time accumulation. However, for a light beam, the same double-slit experimental set-up (with the said changes) should produce interference pattern. These new predictions for photons and light are not captured in the theory devised by Aharonov et al. (2017).

5.2. Experiments for individual electrons and for electron beam

For additional supports, we can run the one- and two-slit experiments with electrons. In this case, the electrons can be (e) an electron beam or (f) the electrons are detected individually. The only change to the experimental set-up is (g) a proper electrically-neutral and highly insulating slit material where (d) the slits should also be the actual openings. With this new change, namely, (g), the experimental results for a double-slit can produce interference pattern (on the screen, s‴) for electrons detected individually after time accumulation, and also for an electron beam (see Fig. 2(c)). On the other hand, no interference pattern (partial nor full) should be observed for the experimental set-up depicted in Fig. 2(b), and these two observations are not new.

The new observations can be measured if the experimental set-up follows Fig. 2(a) such that the partial interference pattern should be obtained regardless of whether the electrons are detected individually (after time integration) or not (for an electron beam). The full interference pattern can be constructed by overlapping the partial interference patterns measured from Fig. 2(a). For example, the first partial interference pattern can be obtained for the set-up with s1 open and s2 closed (see Fig. 2(a)), while the second partial interference pattern can be obtained for the same set-up but with s1 closed and s2 is open. These new predictions for electrons are also not captured in Aharonov et al. (2017).

6. Theoretical details

The analysis given below is based on the experimental set-up discussed above. For example, the interaction between quantum particles (electrons and photons) and the opening in the slit materials is based on classical physics, which is similar to cathode-ray tubes (CRTs) and is sufficient. In particular, the slit materials are selected in such a way that individual electrons and photons interact mechanically with their respective slit material (described above). Hence, our analysis implies that each quantum particle has a well-defined path from the source to the screen. The calculations that treat electrons and photons as waves are well known (Halliday and Resnick, 1988). Here, our theoretical analysis focus on individual detections of photons and electrons.

6.1. Quantitative analysis for photons

We can evaluate the proposition of detecting photons and electrons individually by reconstructing the diffraction based on wave theory. This reconstruction is necessary because the interference pattern (maximum and minimum intensity) produced by a light beam (composed of photons) is due to overlapping light waves that interferes constructively (from two in-phase light waves) and destructively (from two out-of-phase light waves). The mechanism for this well-known interference is completely different from the propositions listed in 1P to 4P. Let us work out the quantitative details. In a single-slit experiment, the incident photon that eventually hit the screen actually got scattered at the slit in such a way that its direction of propagation has changed (the same way as the diffracted ray of a light beam (Halliday and Resnick, 1988)). In this case, the scattered photon by a narrow slit with width, a shall satisfy this condition,

$$\sum_{\mathcal{N}} \frac{a}{2} \sin\theta_{\mathcal{N}} = \sum_{\mathcal{N}} \frac{\ell_{\mathcal{N}}}{2}, \tag{7}$$

to produce the regions of high and low concentrations of photons on the upper-half of the screen, from 0 to $\ell/2$ that correspond to high and low intensity. Here, θ is the angle of deflection from the line normal to the slit, $a/2$ is the position of one of the slits' edges where the center of the slit is set at 0, thus the other edge is at $-a/2$. The positions for the photons to hit the screen is along the length, from 0 to $\ell/2$ on the screen, while $\mathcal{N}$ counts each photon that hits the screen, $\mathcal{N} = 1, 2, \ldots$.

In addition, we have the standard single-slit observation from Eq. (7)—for a given screen length or size, ℓ, the narrower the slit (decreasing a), θ increases, which indicates increasing scattering strength between a photon with the slit's edges. Hence, θ is a measure of this photon-slit scattering strength or magnitude. Next, we need to derive the formula for intensity for the accumulated photons from each photon detected on the screen. This is again similar to wave theory (Halliday and Resnick, 1988) where each ray is replaced by a waving photon that propagates from the slit to the screen.

The photon is a proper waving entity due to electric and magnetic fields attached to it (see Eq. (3)), and is subject to the Heisenberg uncertainty principle. Therefore, each photon does wave with a wavelength, but this wavelength is not responsible for the interference pattern when the photons are detected individually because the interference pattern has got nothing to do with in-phase and out-of-phase interference of two waves. As such, the electric field of the scattered photon can be found from,

$$\sum_{\mathcal{N}} E(\theta)_{\mathcal{N}} = 2\sum_{\mathcal{N}} R_{\mathcal{N}} \sin\frac{1}{2}\phi_{\mathcal{N}}, \tag{8}$$

and after noting $\phi = E(0)/R$ for each photon, we can arrive at,

$$\sum_{\mathcal{N}} E(\theta)_{\mathcal{N}} = \sum_{\mathcal{N}} \left(\frac{E(0)_{\mathcal{N}}}{\frac{1}{2}\phi_{\mathcal{N}}}\right) \sin\frac{1}{2}\phi_{\mathcal{N}}. \tag{9}$$

The intensity for the photons can be calculated by squaring the electric field terms, and the final intensity formula is readily obtained,

$$\sum_{\mathcal{N}} I(\theta)_{\mathcal{N}} = \sum_{\mathcal{N}} I(0)_{\mathcal{N}} \left(\frac{\sin\alpha_{\mathcal{N}}}{\alpha_{\mathcal{N}}}\right)^2, \tag{10}$$

where $I(0)$ is the intensity of the unscattered photon after crossing the single slit. The new angle, $\phi = 2\alpha$ is related to the scattering induced deflection to the incident photon entering the slit, or the picked up phase by the photon after interacting with the slit. This angle can be derived from Eq. (7) after multiplying the factor $\phi/2\pi$ where ϕ is the change in the phase of the waving photon. In particular, larger ϕ implies larger θ or larger scattering strength or magnitude. Therefore,

$$\sum_{\mathcal{N}} a\sin\theta_{\mathcal{N}} = \sum_{\mathcal{N}} \ell_{\mathcal{N}} \frac{\phi_{\mathcal{N}}}{2\pi}, \tag{11}$$

and the change in the phase is given by,

$$\sum_{\mathcal{N}} \phi_{\mathcal{N}} = \sum_{\mathcal{N}} \frac{2\pi a}{\ell_{\mathcal{N}}} \sin\theta_{\mathcal{N}}. \tag{12}$$

Hence, we have proved the relative intensity for the single-slit diffraction from Eq. (10) for photons detected individually where,

$$\sum_{\mathcal{N}} \alpha_{\mathcal{N}} = \sum_{\mathcal{N}} \mathtt{m}_{\mathcal{N}}\pi = \sum_{\mathcal{N}} \frac{\pi a}{\ell_{\mathcal{N}}} \sin\theta_{\mathcal{N}}, \tag{13}$$

and the respective intensity minima and maxima occur for,

$$\mathtt{m} = 1, 2, 3, \ldots, \tag{14}$$

$$\mathtt{m} = \frac{3}{2}, \frac{5}{2}, \ldots. \tag{15}$$

Here, smaller and smaller amount of photons ($\mathcal{N}$) correspond to larger and integer $\mathtt{m}$, while larger and larger amount of photons are associated to smaller and non-integer $\mathtt{m}$ (excluding the center maximum). In addition, we cannot calculate θ nor ℓ for each photon. Now, for the two-slit experiment with the slit material that does not let the photons to pass through (via transmission and/or reflection or by any other process) in regions other than the opening (the slits), then the interference pattern cannot be observed for photons accumulated after detecting them individually. In this case, each slit (from a two-slit material) is subject to Eqs. (10), (13) and (14).

If the individual photons are allowed to pass through (via reflection and transmission), one-at-a-time, through the slit material (also with two slits) between the slits (diffraction grating), then one should be able to observe the interference pattern from the time-integrated intensity. In this second case with two slits, the intensity for the interference pattern is given by (following the same procedure given in (Halliday and Resnick, 1988)),

$$\sum_{\mathcal{N}} I(\theta)_{\mathcal{N}} = \sum_{\mathcal{N}} I(0)_{\mathcal{N}} \left[\cos^2\beta_{\mathcal{N}}\right] \left(\frac{\sin\alpha_{\mathcal{N}}}{\alpha_{\mathcal{N}}}\right)^2, \tag{16}$$

where,

$$\sum_{\mathcal{N}} \beta_{\mathcal{N}} = \sum_{\mathcal{N}} \frac{\pi d}{\ell_{\mathcal{N}}} \sin\theta_{\mathcal{N}}. \tag{17}$$

Both Eqs. (16) and (17) are sufficient to capture the formation of interference pattern from the photons detected individually for the grating that contains two slits where d is the spacing between the slits. Here, β is the additional phase picked up by each photon that crosses the regions other than the two grooves. For each parameter that carries the subscript, $\mathcal{N}$, implies the parameter is not a constant even for each scattered photon or electron (see below). The angles, α and β picked up by each photon due to scattering at the slits refer to the change in the direction of the photon propagation.

Note this and note this carefully, individually detected photons can produce the interference pattern (after time integration) as sketched in Fig. 1(a) and (b) if and only if the slits are diffraction slits and the slit material is optically transparent (that gives rise to internal reflection and refraction). If the slit material is optically non-transparent such that it does not permit photons to pass through, then the slits have to be slit holes. In this case, the interference patterns sketched in Fig. 1(a) and (b) are not observable for individually detected photons. This new experimental set-up (using optically non-transparent material with slit holes) can only produce interference pattern for electromagnetic waves, but not for individually detected photons (after time integration). No single-photon experiments, including the recent report (Aspden et al., 2016), have used optically non-transparent slit material with slit holes to detect single photons.

Note this, for a light beam, Proposition 2P is irrelevant because the material with two slits or the transparent grating material with two grooves (two 'slits') can produce the interference pattern from two waves due to their in-phase and out-of-phase interference. It should be apparent that $\beta = 0$ because $\sin\theta$ in Eq. (17) is zero for the first case with two slits in a material that does not allow photons to exit the slit material in regions other than the two slit openings. All the analysis presented here readily reduces to the standard formalism given in Halliday and Resnick (1988) if one switches to diffracted light rays that interferes destructively (out-of-phase) and constructively (in-phase).

6.2. Quantitative analysis for electrons

Let us first consider a single-slit experiment with electrons detected individually (with one electron at a time). Detecting each incident electron after it got scattered at the slit(s) is similar to the formalism presented for photons that are also detected individually, except in this case, the source of the scattering is the electron(incident)-electron(slit) interaction. Hence, we can readily consider the step potential (provided by the slit) as a simple example to capture the scattering of each incident electron. Letting the potential, V experienced by an incident electron approaching the slit, one can construct the one-dimensional Schrödinger equation (from Eq. (2)) for that scattered electron (after interacting with the slit),

$$\sum_{\mathcal{N}} \frac{\mathrm{d}^2\Psi_{\mathcal{N}}}{\mathrm{d}x_{\mathcal{N}}^2} + \sum_{\mathcal{N}} \frac{2m(E_{\mathcal{N}} - V)}{\hbar^2}\Psi_{\mathcal{N}} = 0, \tag{18}$$

where the electron mass, m_e and V are constants for each incident electron, $\hbar$ is the Planck constant, E is the energy of the incident electron, which is obviously much larger than V (or $E > V$) so that the electron shall never be trapped by the slit. The wavenumber after scattering by a single slit is,

$$\sum_{\mathcal{N}} k_{\mathcal{N}} = \sum_{\mathcal{N}} \frac{\sqrt{2m_e(E_{\mathcal{N}} - V)}}{\hbar}, \tag{19}$$

which is a real number as it should be, and the general solution for the stated Schrödinger equation is trivial,

$$\sum_{\mathcal{N}} \Psi_{\mathcal{N}} = \sum_{\mathcal{N}} \mathtt{A}_{\mathcal{N}} \exp\left[\mathrm{i}k_{\mathcal{N}}x_{\mathcal{N}}\right], \tag{20}$$

where each Ψ is the wavefunction for an electron that may or may not be scattered and shall eventually hit the screen, A is the amplitude and the scattered momentum for the electron is $\hbar k$. We are not concerned with the physics prior to scattering because they are controlled such that the electrons (or photons) have consistent energy and equal probability along the width of one (a) or two ($2a$) slits.

To calculate the intensity for the electrons detected individually in a single-slit experiment, we need to recall Eq. (8) and rewrite it as follows,

$$\sum_{\mathcal{N}} \psi(\theta)_{\mathcal{N}} = 2\sum_{\mathcal{N}} R_{\mathcal{N}} \sin\frac{1}{2}\phi_{\mathcal{N}}, \tag{21}$$

and $\phi = \psi(0)/R$ for each electron and after noting that the intensity is proportional to $|\psi(\theta)|^2$, we can arrive at the same equation given in Eq. (10) for electron accumulated one at a time. Here, we have invoked another wavefunction for the same electron, $\psi(\theta) \neq \Psi$ to capture the changes to the direction of each electron due to scattering at the slit. Note this, the magnitudes of all the variables in Eq. (10) for each electron are of course different from those of each photon. Nevertheless, each electron and photon with different magnitudes (for those parameters) accumulate to produce diffraction as defined by Eq. (10). If we repeat the experiment with two open slits, the observed interference pattern follow Eq. (16) where Eq. (16) remains exactly the same for electrons detected individually, which of course can be derived directly from Eq. (21).

There is an interesting twist here for electrons hitting the screen one-by-one or one at a time when one of the slits is open, while the other is closed (see Fig. 2(a)). This situation is different from that of the experiment that contains only one slit (see Fig. 2(b)) as discussed qualitatively earlier and is captured by Eq. (10). In this case as depicted in Fig. 2(a), Eq. (16) remains the same but Eq. (17) reads,

$$\sum_{\mathcal{N}} \beta_{\mathcal{N}} = \sum_{\mathcal{N}} \frac{\pi(d/y_1)}{\ell_{\mathcal{N}}} \sin\frac{\theta_{\mathcal{N}}}{y_2}. \tag{22}$$

Here, d and $\theta_{\mathcal{N}}$ have been replaced by d/y_1 and $\theta_{\mathcal{N}}/y_2$ where $(y_1, y_2) > 1$, which depend on the type of slit material. For example, for the slit material that effectively minimizes the electron(incident)-electron(slit-2) interaction gives $(y_1, y_2) \to \infty$ so that $\beta = 0$.

6.3. Summary

Theoretical plots based on Eq. (16) for both electrons and photons follow exactly the same plots given in Halliday and Resnick (1988). The primary new results in this report are the construction of the physical mechanisms that are responsible for the following two `predicted` observations, which are completely new (both the predicted observations and their physical mechanisms).

(`ai`) The absence of interference pattern in a double-slit experiment for photons (detected individually).

(`bii`) The formation of partial interference pattern for both individual electrons and electron beam.

See the following explanations for these two [(`ai`) and (`bii`)] constructed physical mechanisms. For photons (see (`ai`) above), the double-slit experiment (using non-transparent slit material with slit holes) cannot produce any interference pattern for photons detected individually and after time integration. On the other hand, the changed experimental set-up (using non-transparent slit material with slit holes) can produce the required interference pattern if one uses electromagnetic waves. In other words, the interference pattern produced using the transparent diffraction slits for both single photons and electromagnetic waves have the same mechanism, which is caused by photons transmission, internal reflection and refraction. This means that, interference pattern cannot form for single-photon detection (after time integration) if one uses non-transparent slit holes. However, non-transparent slit holes can produce interference pattern for electromagnetic waves due to this well-known classical mechanism—constructive and destructive interference of waves.

The physical mechanism to produce interference pattern for electrons is completely different (see below) from that of single-photon detection and electromagnetic waves. For electrons (see (`bii`) above), the double-slit experiment has to have slit holes (openings) but the slit-material should be electrically neutral and insulating. Thus, the interference pattern using electrons (massive and charged) is caused by mechanical-like Coulomb interaction [electron(source)-electron(slit)] at the slit-hole's edges. The interaction is mechanical-like because the electrons are relatively of low kinetic energies, and the slit-material is electrically neutral and highly insulating. For electrons (either detected individually or otherwise), one can obtain the partial interference pattern with one slit closed (following Fig. 2(a)). The full interference pattern can be constructed by overlapping the other partial interference pattern obtained from Fig. 2(a) after reversing the open-close arrangement. We cannot prove the uniqueness of these differing mechanisms (for electrons and photons) with equations nor calculations. For example, we can reproduce all of the above results from Eq. (16) alone by activating and adjusting the parameters where for pure waves, we just remove the summation sign and $\mathcal{N}$, replace ℓ with wavelength, λ and start adjusting α and β. For individual detections, we just need to adjust α and β for each particle. Thus, we have no other choice but to rely on the experimental proof.

7. Conclusions

We have attempted to explain the origin of interference patterns for photons and electrons by constructing the appropriate propositions on the basis of well-known and existing interactions. The propositions also contain information that can be used to properly set-up the one- and two-slit experiments. Here, electrons are assumed to interact with electrons from the slit-material. This interaction is symmetric if the slit-material has only one embedded slit, whereas, an asymmetric interaction is expected if the material has two slits (regardless of whether one of the slits is open or closed). Consequently, one can obtain a partial interference pattern if s1 is open while s2 is blocked. As such, we can generate the complete fringes by overlapping the separate results after time integration (for individual detections). These separate results refer to the partial interference pattern or the partial intensity obtained from 's1 is open while s2 is blocked' and the other partial intensity is obtained from 's2 is open while s1 is blocked', which are then overlapped to form the complete fringes for electrons.

In contrast, two waving groups of photons (one group from s1, and the other from s2) need to interfere constructively and destructively to produce the fringes on the screen. Overlapping the intensity peaks from s1 (s2 blocked) and s2 (s1 blocked) does not generate the complete interference pattern for photons. However, the formation of interference pattern from the time-integrated intensity of individual photons is similar to electrons. In other words, it is postulated (see Proposition 2P) that the interaction between a photon and both slits' edges (due to reflection and transmission) give rise to the interference pattern for photons (detected individually or otherwise) such that the slit material (optically transparent) allows the photon to exit the slit material in the region other than the slit opening.

Apart from that, the material with embedded slit(s) also need to be experimented to satisfy these requirements, (i) for electrons—the slit-material should stop the electrons from passing through (via tunneling or conduction or by any other process) in regions other than the opening (the slits), and (ii) for photons—the material should block all photons from passing through (via transmission or reflection or by any other process) in regions other than the slits. In summary, we have provided the proper and correct resolution to the double- and single-slit experiments for both photons and electrons, either detected individually or otherwise. In addition, our quantitative analysis did not violate the well-established diffraction and interference pattern produced from interfering in-phase and out-of-phase light waves.

CRediT authorship contribution statement

Andrew Das Arulsamy: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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