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Differentiating the Superposition Principle from the Measurable Superposition Effects in Interferometry

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Abstract

The *physical interaction processes* behind the emergence of dark and bright fringes registered by the detectors at the output of optical interferometers is explained. This knowledge should be helpful to interferometrists to make better physical interpretations of their data. The *belief* in mysterious “interference of single indivisible photon” will disappear once we recognize that the spatial or temporal energy re-distributions are generated by the physical transformation experienced by the detecting molecules drawing energy from all the light beams. The molecules could be photodetectors at the interferometer output, or the beam combining dielectric boundary. The superposition principle (SP), represented by the *linear* mathematical sum of two or more wave amplitudes, does not represent an observable phenomenon. The superposition effect (SE), represented by the *non-linear* square modulus of the joint dipolar stimulation of the detectors by all the superposed waves, is observable. We present two laboratory experiments to clarify these points. Both classical beam combiners and quantum detectors are capable of generating superposition fringes of intensity variations. The logic of “quantumness” of light is narrowly relevant only when a quantum detector deciphers the fringes; it is not valid for classical beam combiners. We will also discuss “entanglement” based on these experiments.

Keywords: superposition principle, superposition effect, single photon interference, response of detecting dipoles, Mach-Zehnder interferometer

1. Introduction

The objective of this chapter is to use a simple classical Mach-Zehnder interferometer separately under *spatial-fringe-mode* (Poynting vectors noncollinear in the output) and *scanning-fringe-mode* (Poynting vectors perfectly collinear in the output). The purpose is to demonstrate that “single photon interference” is a noncausal interpretation of the light-matter interaction process, where light energy absorbed by a detector array represents bright fringes and nonabsorption represents dark fringes. The process is not due to some mystical arrival and nonarrival of “photons” that defies the diffractive light propagation physics. The light propagation physics cannot remain strictly valid everywhere except in human-constructed

interferometers and Young's double-slit diffractometers. We are using mathematical formalism, which we have accepted for a couple of centuries. We support our arguments based upon *strict causality built into our mathematics* and corroborated by measured data. This chapter considers light-matter interaction process exclusively from the standpoint of semi-classical model, where light is treated as classical electromagnetic waves and light detecting atoms and molecules as quantum entities that have discrete quantum mechanical binding energy levels (or bands) with finite transition probabilities.

In Sections 2.1 and 2.2, we use simple Mach-Zehnder interferometers with the Poynting vectors of the two combined output beams under (i) noncollinear and (ii) strict collinear conditions. The experiments demonstrate that the two incident signals from the two opposite sides of the beam combiner *must be simultaneously present to generate the observed superposition effects*. The simple mathematical formalism tells us that wave amplitudes by themselves never re-arrange their spatial or temporal energy distribution. They continue to propagate unperturbed by each other's physical presence. We have called this wave property, noninteraction of waves (NIW). In Section 3, we show a simple derivation of the Einstein's photoelectric equation as a superposition effect congruent with the semi-classical model. Since the basic mathematical formalism of Quantum Mechanics (QM) is correct, we must learn to avoid being trapped in the century-old and *un-necessary* circular arguments behind diverse mystical interpretation of Quantum Mechanics (QM). In Section 4, we describe this briefly by underscoring that the so-called "Measurement Problem" of QM is a fundamental "Information Retrieval Problem" out of all experiments, which cannot be solved by promoting elegant and beautiful mathematical theorems. It will require consistent and iterative attempts on the part of generations of scientists to visualize the invisible interaction processes going on in nature. Experimental data driven "evidence-based science" is the best approach to unravel nature's causal interaction processes while guided by strictly causal mathematical rules. Unfortunately, most of the details of the micro interaction processes are still beyond our capability to visualize directly. The problem is further compounded by the fact that the beautiful mathematical logics are inventions by the "subjective" neural networks of the human species.

2. Differentiating the superposition principle from the measurable superposition effect

2.1 Formulating the basic superposition equation

The most neglected issue in current books and literature is that the co-propagating and cross-propagating wave amplitudes pass through each other completely unperturbed (uninfluenced) by each other's presence in the absence of interacting materials. In other words, the superposed wave fronts by themselves do not generate observable interferometric fringes whenever they are superposed. This is noninteraction of wave (NIW) amplitudes [1]. Alhazen observed this phenomenon almost 1000 years ago using a set of candles and a pinhole camera [2]. Huygens underscored this in his book [3] around 1667. This is why it is important to remember that even quantum electrodynamics acknowledges that photon-photon interaction cross section is immeasurably small [4]. In fact, Dirac mathematically found that "different photons do not interfere with each other" (NIW?). Unfortunately, he introduced the noncausal notion that "a photon interferes only with itself" [5]. This assertion is noncausal because interference fringes always appear as some

physical transformation in a detector induced by more than one amplitude signals carrying different phase information. Further, the dark fringes are not due to nonarrival of “photons.” It is because the joint stimulations by the out-of-phase E-vectors (only when equal amplitude!) fail to stimulate the detecting dipoles, and hence, the field energy cannot enter into the detecting dipoles’ *quantum cups*. We always represent the superposition equation by two separate amplitude terms, each containing its own phase factor representing separate and independent oscillations of the E-vectors. A single stable elementary particle (here, a “photon”) could not be *multivalued* in its critical dynamic parameters at any single moment. Further, in the *absence of any other interacting force(s)*, it should not, by itself, appear or disappear in some specific physical location for some specific instrumental alignments made by humans to generate dark and bright fringes. In writing supposition equation, we always completely ignore the mathematics necessary to represent inherent diffraction physics of light waves. This is only partially correct for collimated beams traveling only short distances. Under this assumption, we neglect spatial evolution of complex amplitudes of the two waves. Photons cannot independently change their trajectories. Propagation of EM waves is rigorously given by Maxwell’s wave equation and Huygens-Fresnel diffraction integral. Noninteraction of photons or generalized noninteraction of wave (NIW) [1] is equivalent to the statement that the linear mathematical superposition principle (SP) *does not represent an observable phenomenon*. It is a correct mathematical starting point to derive the *observable superposition effect (SE)* as the *nonlinear square modulus* of the expression for the linear superposition principle. In spite of this existing knowledge, somehow we get systematic training to accept that individual “indivisible light quanta” interfere by themselves. The phrase, “indivisible light quanta,” represents energy “ $h\nu$,” a quantum cup of energy that is exchanged between quantized materials and classical waves. The mathematical expression “ $h\nu$ ” *is devoid of phase information*. Note that our equation representing superposition phenomenon consists of *two or more superposed waves with different amplitudes and phases carried by separate waves*. Insertion of “bra” and “ket” symbols on to the complex amplitude terms fails to accommodate the physical properties behind *the spontaneous and perpetually diffractive EM waves* through any medium or instrument (evolving spatial amplitudes, phases, and Poynting vectors). This diffractive propagation property has been correctly captured by classical diffraction integrals, which form the very foundation of classical optics since its inception in 1817 by Fresnel [6].

In a typical two-beam interferometer, like Mach-Zehnder, the classical expression for the superposition of two replicated output plane waves, crossing through each other at a small angle, can be expressed as the traditional *Mathematical Supposition Principle*:

$$E(t, \tau) = E_1(t) + E_2(t + \tau) = a_1 e^{i2\pi\nu(t-\tau/2)} + a_2 e^{i2\pi\nu(t+\tau/2)} \quad (1)$$

In **Figure 1**, we have assumed that relative propagation delay along the two independent paths in the interferometer is zero by virtue of physical alignment when they intersect at the $X = 0$, the origin where the detector array is placed to register the fringes. The intensity variation is along the X-axis following the relative path delay, $\tau = 2(x \sin \theta / c)$.

Eq. (1) represents the well-known mathematical superposition principle (SP). SP is not directly observable. Generation of observable superposition effect (SE), or data, involves a series of complex physical interaction processes. The data are generated as some physical transformation triggered by energy exchange between some interactants in our chosen instrument. The interactants are photoresponsive material dipoles and EM waves. First, the material dipoles in the detector array

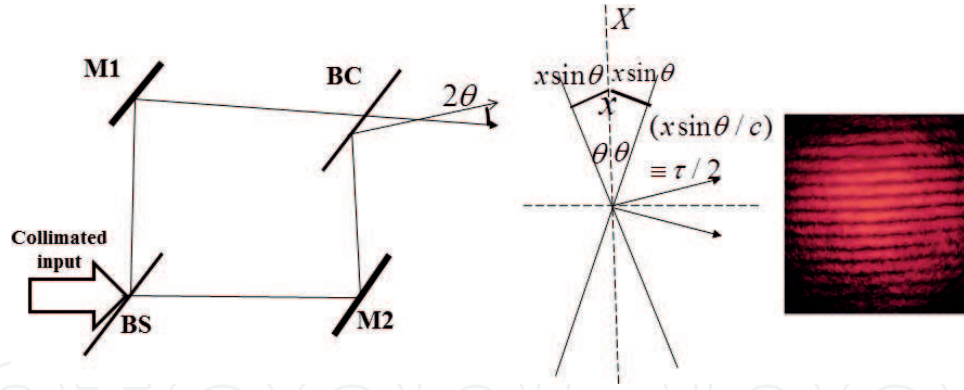


Figure 1. A Mach-Zehnder interferometer in spatial-fringe-mode, illuminated with a collimated beam (left sketch). The two output beams intersect each other at the plane of a detector array (X-plane; middle sketch). The total relative path delay is $\tau = (2x \sin \theta)/c$. The linear dark-bright fringes oscillate along the X-axis (right photograph).

experience dipolar stimulations by both the superposed EM waves. The incident optical frequency ν has to be resonant with the allowed quantum transition. This *dipolar stimulation parameter* $\chi(\nu)$ is the *linear* (first order) polarizability. The traditional photo effects happen with the release of quantum mechanically bound photoelectrons to free space or internally to the conduction band. The older method used to be the dissociation of quantum mechanically bound Ag-Halide molecules in photographic plates. Therefore, the physical amplitude-amplitude stimulation effect, $\psi(t, \tau)$, should be explicitly recognized, as it is done by various semi-classical models [7–9]. Therefore, the real *physical superposition principle* should be expressed as the joint dipolar stimulations:

$$\begin{aligned} \psi(t, \tau) &\equiv \chi(\nu) E_{\text{total}}(t, \tau) = \chi(\nu) E_1(t) + \chi(\nu) E_2(t + \tau) \\ &= \{\chi(\nu) a_1\} e^{i2\pi\nu(t-\tau/2)} + \{\chi(\nu) a_2\} e^{i2\pi\nu(t+\tau/2)} \\ &= \chi(\nu) [a_1 e^{i2\pi\nu(t-\tau/2)} + a_2 e^{i2\pi\nu(t+\tau/2)}]; \text{ frequency band very narrow.} \end{aligned} \quad (2)$$

(We are assuming here that the incident light beam is linearly polarized. Further, we are neglecting interactions of light with any anisotropic medium. This is to avoid unnecessary complexity in mathematics, which can divert our attention from the simple core issue that superposition effects become manifest only when some material medium undergoes observable physical change under the simultaneous joint stimulations by multiple waves.)

The interference fringe data $D(t, \tau)$ are generated *after the energy transfer process is executed* by the stimulated photosensitive dipoles, which is the square modulus of Eq. (2):

$$\begin{aligned} D(t, \tau) &\equiv |\psi(t, \tau)|^2 = \chi^2(\nu) [a_1^2 + a_2^2 + 2a_1 a_2 \cos 2\pi\nu\tau] \\ &= \chi^2(\nu) (a_1^2 + a_2^2) [1 + \gamma(\tau) \cos 2\pi\nu\tau]; \gamma(\tau) \equiv \{2a_1 a_2 / (a_1^2 + a_2^2)\} \\ &= 2\chi^2(\nu) a^2 [1 + \cos 2\pi\nu\tau]; \text{ only when } a_1 = a_2. \end{aligned} \quad (3)$$

This nonlinear square modulus interaction process cannot be executed by superposed linear fields in the absence of interacting materials. Accordingly, Eq. (1) does not represent any physical interaction process. *Therefore, we should restrain ourselves in assigning interpretations about the physical nature of light using this unobservable amplitude, Eq. (1), while, holding in mind, the observable data represented by the energy Eq. (3).* The proper linear physical superposition principle, representing joint amplitude stimulations of a detector, should always be represented by Eq. (2) to avoid making noncausal interpretations of observable

superposition phenomena of nature. The best rational and physical interpretation that we can assign to Eq. (1) is that electromagnetic waves can co-exist within the same physical volume, while they cross-propagate, or co-propagate, independent of each other, as long as the medium is linear and noninteracting. This is the generalized noninteraction of waves (NIW), mentioned earlier valid for all propagating wave phenomena. For details, see Refs. [1, 10].

Let us appreciate that *the same single photon cannot represent two different physical beams*. Let us also note that in Eq. (3), the fringe visibility, $\gamma(\tau) \equiv \{2a_1a_2/(a_1^2 + a_2^2)\}$, is influenced by the two different amplitude parameters, and further, the fringe oscillation is influenced by two different phase factors, $\exp[i2\pi\nu(t - \tau/2)]$ and $\exp[i2\pi\nu(t + \tau/2)]$, which are manifest in the oscillation of the fringes through $\cos 2\pi\nu\tau$. We have mentioned that no *stable elementary particle* can carry more than one unique value for any of its physically essential (critical) dynamic parameters at any moment that define the existence of the entity. Thus, as per our causal equation, each one of the two signals we generate in an interferometer must be a physically *real and independent physical signal*, whether they are interpreted as classical EM wave packets or quantum mechanical “indivisible light quanta.” Each wave plays separate important role in generating the final fringe pattern. Just one “photon,” from one or the other wave, cannot dictate the emergence of the fringes as it does not have the other necessary parameter to interact with while stimulating the detecting dipoles. The concept of interaction-free superposition effect does not advance our intention of deeper enquiry of phenomena in nature. Natural phenomena happen only through diverse interactions between different entities.

Fringes of perfect unit visibility are almost impossible to achieve in practice. The fringe visibility is $\gamma(\tau) \equiv \{2a_1a_2/(a_1^2 + a_2^2)\} = 1$, only when $a_1 = a_2$ accurate to a tiny fraction of the energy carried by a single photon, $h\nu = (6.63 \times 10^{-34} \text{ J} \cdot \text{sec}) \times (5.83 \times 10^{14} / \text{sec}) = 3.86 \times 10^{-19} \text{ J}$ (for green light). This is a staggeringly small energy. We do not have any energy meter that can even come close to *directly* measure such a miniscule energy *decisively*. Further, the final beam combiner must have exactly T/R = (0.5/0.5), accurate to the single photon energy. A vendor will never agree to sell such a beam splitter, as they do not have the necessary technology to measure energy with such an accuracy. In other words, the fringe visibility, $\gamma(\tau) \equiv \{2a_1a_2/(a_1^2 + a_2^2)\}$, must be computed by separately measuring the two intensities, a_1^2 and a_2^2 , for the two real beams and then compute a_1 and a_2 . Eq. (3) has been experimentally validated innumerable times during the past two centuries. This experimentally valid mathematical Eq. (3) dictates that the superposition of two real and separate beams generates the interference fringes, and they cannot be generated by a single photon out of only one of the two beams.

Emergence of dark fringes: To strengthen the previous points further, we explore the physical processes behind the emergence of alternate dark fringes between the bright fringes. Mathematically, perfect dark fringes imply $D(t, \tau) = 0$. Superposition effect is *local* since the bright and dark fringes continuously vary in space and the size of the detecting dipoles is miniscule ($\sim \text{Angstrom}^3$) [11]. We all accept that the cosine intensity variation in the fringes is due to the phase factor $\cos 2\pi\nu\tau$, as we keep changing the relative path delay τ . $D(t, \tau)$ is a minimum whenever $2\nu\tau$ becomes an odd multiplier to π , making $\cos 2\pi\nu\tau = -1$. However, the only way $D(t, \tau)$ could be exactly zero is when $a_1 = a_2$, making the visibility factor $\gamma(\tau) = 1$. It is then obvious through the rigorous mathematical logic of Eq. (3) that dark fringes cannot be due to “nonarrival of indivisible photons” [12, 13] in these locations. Implication of “single photon interference” is that the detector’s role is only to register the arrived energy without any participating in any way *in the superposition interaction*

process itself. This noncausal assumption has led to the emergence of the *belief* behind *nonlocality*, *noncausality*, etc. This faithful belief in *nonarrival* of indivisible photons or of particles at dark fringe locations still dominates our physics community. It is then a fair question to ask whether we should trust more than a century old data validated Eq. (3) or the *unnecessary* mystical interpretation proposed after the advent of quantum mechanics in 1925. In the face of the reality that all theories are approximate and incomplete, we can keep on advancing science only by accepting any experimentally validated mathematical theories, which do not promote noncausal and incongruent interpretations. We should use such “evidence-based theories” *as intermediate steps* toward constructing better and better theories. In other words, QM is incomplete since it has been constructed to predict only the final measurable outcome *without any attention to understand the detailed interaction processes* that precede the QM transitions.

Most of the self-contradictory interpretations of the superposition principle will become unnecessary once we accept the hybrid model for photons. Atoms and molecules do emit discrete quantity of energy $h\nu$ during each allowed quantum transition. However, the $h\nu$ packet of energy immediately evolves into a perpetually propagating EM wave while spreading out diffractively, as it has been modeled classically (Ch. 10 in Refs. [1, 14]). During energy absorptions, the quantum dipoles function as “quantum cups” and they fill up that cup with the required amount of energy $h\nu$ out of the classical waves propagating through them. If the flux density within its stimulated quantum-cup volume is below $h\nu$, then there will be no photoelectric transition. This is a difficult experiment since one has to reduce the energy flow in reliable calibrated steps toward the single photon energy of $3.86 \times 10^{-19} \text{J}$. Current technology does not offer us any energy meter that can *directly* measure such a miniscule amount of energy. The release of a single bound photoelectron does validate the absorption of $h\nu$ amount of energy, since QM is essentially correct. However, it does not guarantee the existence and presence of *indivisible photons*. Each measured *click* out of our photon counting electronic system represents a burst of current pulse consisting of hundreds of millions of amplified electrons. As electrons are quantized particles and always bound quantum mechanically, their emission process steps will have to be discrete. Discreteness of the emitted electrons does not automatically validate the discreteness of the propagating EM wave energy. *Quantum formalism does not require that quantum transition can be affected only by another quantum entity having the right amount of energy to donate*. Striking stones create sparks. This is a complex energy exchange process, but nonetheless, it consists of a discrete series of quantum excitation and de-excitation processes triggered originally by the *mechanical energy of hands*. The validity of Boltzmann’s rule of population density, dictated by classical *thermal collisions*, is rigorously obeyed by quantum systems that experience thermal collisions.

The author believes that nature abhors magic and mysticism. Physics has been advancing based on hard causality guided by rigorous mathematical logics but as a guiding tool only. Human invented mathematics cannot dictate nature how she ought to behave.

2.1.1 Recognizing noninteraction of waves (NIW) from the expression for the real physical superposition principle

We have already defined real *physical superposition principle* as Eq. (2), which represents the *linear amplitude* stimulation of the detecting dipole induced by both the superposed fields simultaneously. The energy transfer to the detector is given by

the square modulus of Eq. (2), as presented in Eq. (3). Note that the polarizability $\chi(\nu)$ in Eq. (2) and $\chi^2(\nu)$ in Eq. (3) can be taken out of the amplitude and the intensity terms, respectively, as a common factor, provided χ does not vary with ν and t . This is allowed by the generic mathematical rule. This mathematical rule, while bears out in many situations, deprives us, appreciating the deeper interaction processes in nature. The t -independence of $\chi(\nu)$ is almost guaranteed whenever the material properties are stable in time. However, the frequency independence is never rigorously valid, since response of all materials depends upon the resonant frequency (quantum transition levels or bands in atoms and materials). We know that the detectivity of broadband solid-state detectors varies with frequency. However, when the spread of the wave frequency in the incident beam is extremely narrow, $\chi(\nu)$ can be treated as a constant for that frequency and treated as a constant common factor.

Let us now pay close attention to the third line of Eq. (2). With $\chi(\nu)$ taken out as a common factor, the expression within the parenthesis *may imply* that the two EM wave amplitude components are *summing themselves* to create the *interference* of waves. We can easily make this very serious conceptual mistake guided by the allowed abstract mathematical rules. Mathematical rules are human-invented logics. They do not always capture nature's logic. The linear superposition of amplitudes, as already underscored, does not generate any observable effect by themselves, in the absence of some interacting materials. This is why appreciating noninteraction of waves (NIW) is of such critical importance [1].

2.2 Pure “classical” interference (re-direction of energy) by a “passive” beam combiner

The interferometer arrangement we have utilized in the previous section (Figure 1) could be described as an interferometer in *spatial-fringe mode* [15, 16]. The Poynting vectors of the two propagating beams in Figure 1 are *noncollinear*. In this section, we analyze an alternate arrangement where the Poynting vectors of the two pairs of output beams, generated by the output beam combiner BC, are perfectly collinear and coincident to each other. Such superposed parallel beams will continue to propagate with the same relative, but fixed, path delay generated within the interferometer (Figure 2). To keep the mathematical analysis simple, as in the last section, we are assuming that the relative physical path delay between the two beams is zero on arrival on the proper dielectric-coated surface of the BC. To

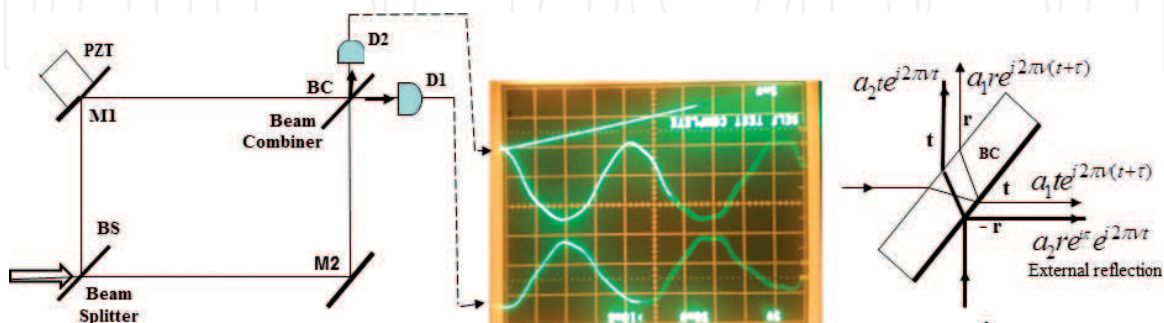


Figure 2. A Mach-Zehnder interferometer in scanning-fringe-mode, illuminated with a collimated beam (left sketch). The Poynting vectors of the two pairs of output beams are perfectly collinear (right sketch). (For clarity of presenting mathematical expressions, the ray-traces are shown spatially separate. In real experiment, they are coincident.) The time-varying fringes can be observed for both the output ports D1 and D2 (middle photo), by scanning the mirror M1. The top-tilted linear trace in this photo represents the scanning voltage applied to the mirror M1. In this set up, the functional physical property of the 50% beam combiner BC oscillates between 100 and 0% transmittance (or reflectance). When D1 detector receives the maximum energy, D2 receives minimum energy [15, 16].

observe energy oscillating fringes under this condition, one has to scan one of the two mirrors with a piezo-electric drive to introduce the temporally oscillating path delay τ . Such interferometer arrangement, in *scanning-fringe-mode*, is quite common in today's lab.

As argued in the above section, the observable superposition effect can become manifest only through light-matter interaction. For a scanning-fringe interferometer, the interaction is between the dielectric boundary and the *two superposed wave amplitudes from the two opposite sides of this boundary material layer*. This is a pure classical boundary value problem for EM waves, which was actually solved by Fresnel even before the development of Maxwell's wave equations. Fresnel found that for the external reflection (towards the direction of lower refractive index), the wave amplitude suffers a π phase shift [1, 17]. The light-matter amplitude-amplitude stimulation is facilitated by the classical linear bulk polarizability $\chi(\nu)$ of the dielectric boundary materials. Here, this $\chi(\nu)$ is for bulk classical dipole polarizability. It is different from that $\chi(\nu)$ for dipoles undergoing QM transition, as in Eqs. (2) and (3), even though they are both *linear*. Then, the joint stimulation of the boundary layer induced by the right-going and the up-going beams, respectively, is:

$$\begin{aligned}\psi_{Rt.}(t, \tau) &\equiv \chi(\nu)E(t, \tau) = \chi(\nu)E_1(t + \tau) + \chi(\nu)E_2(t) \\ &= \{\chi(\nu)a_1t\}e^{i2\pi\nu(t+\tau)} + \{\chi(\nu)a_2re^{i\pi}\}e^{i2\pi\nu t} \\ &= \chi(\nu)[a_1te^{i2\pi\nu(t+\tau)} - a_2re^{i2\pi\nu t}]; \text{ frequency band very narrow.}\end{aligned}\quad (4)$$

$$\psi_{Up.}(t, \tau) = \chi(\nu)[a_1re^{i2\pi\nu(t+\tau)} + a_2te^{i2\pi\nu t}]; \text{ frequency band very narrow.} \quad (5)$$

Assuming that the dielectric boundary layer is approximately loss-less, we can assume that $\chi^2(\nu) = 1$. Then, the detectable energies in the right-going and up-going beams, respectively, are:

$$\begin{aligned}D_{Rt.}(\tau) &\equiv |\psi_{Rt.}(\tau)|^2 = |[a_1te^{i2\pi\nu(t+\tau)} + a_2re^{i\pi}e^{i2\pi\nu t}]|^2 \\ &= [(a_1^2t^2 + a_2^2r^2) - 2a_1a_2tr \cos 2\pi\nu\tau] \\ &= a^2[1 - \cos 2\pi\nu\tau]; \text{ only if } r^2 = t^2 = 0.5 \text{ and } a_1^2 = a_2^2 = a^2\end{aligned}\quad (6)$$

$$\begin{aligned}D_{Up.}(\tau) &\equiv |\psi_{Up.}(\tau)|^2 = |a_1re^{i2\pi\nu(t+\tau)} + a_2te^{i2\pi\nu t}|^2 \\ &= [(a_1^2r^2 + a_2^2t^2) + 2a_1a_2tr \cos 2\pi\nu\tau] \\ &= a^2[1 + \cos 2\pi\nu\tau]; \text{ only if } r^2 = t^2 = 0.5 \text{ and } a_1^2 = a_2^2 = a^2\end{aligned}\quad (7)$$

From the very last lines of the energy, Eqs. (6) and (7), one can easily recognize that, under the ideal conditions of $r^2 = t^2 = 0.5$ and $a_1^2 = a_2^2 = a^2$, the sum total energy of the two beams, incident on the beam combiner from the opposite sides, remains constant, even though each output is oscillating between zero and $2a^2$:

$$D_{Rt.}(\tau) + D_{Up.}(\tau) = 2a^2, \text{ with } a_1^2 = a_2^2 = a^2 \quad (8)$$

The implication is that a passive 50% beam splitter can dynamically keep changing its effective physical transmittivity, or reflectivity, between zero and one. The photo at the center of **Figure 2** is an experimental demonstration of this fact. A dual trace oscilloscope simultaneously displays the output of D1 and D2. While they are undergoing sinusoidal oscillation in displayed energy, the two traces are complementary to each other, preserving the rule of energy conservation. This simple classical *superposition effect* does not have any connection with quantum physics, since the beam splitter is purely a linear classical optical element. It is

not undergoing any quantum transition or generating the fringes due to quantum absorption of energy. As mentioned before, the readers should note that currently we do not have technology to precisely set the conditions $r^2 = t^2 = 0.5$ and $a_1^2 = a_2^2 = a^2$ accurate to that of a *single photon energy*, $h\nu = 3.86 \times 10^{-19}\text{J}$. Accordingly, the claims that one can let a perfectly measured single photon incident on a beam combiner and then detect its appearance in either the port D1, or the port D2, must be taken with a “grain of salt.” Recall that our counting ability of quantum mechanically released electrons does not make EM radiation quantized. Dirac’s quantization of EM wave cannot *localize photons*; however, we have been generating highly localized, in time and space, laser energy as femto second pulses. The photons as linear superposition of finite or infinite set of Fourier modes are not a causal model of physics because of noninteraction of waves.

The conservation of energy remains true even when the conditions $r^2 = t^2 = 0.5$ and $a_1^2 = a_2^2 = a^2$ are not met. From the sum of the second lines of Eqs. (6) and (7), one can again derive that the total energy ($a_1^2 + a_2^2$) is still conserved:

$$\begin{aligned} D_{Rt.}(\tau) + D_{Up.}(\tau) &= (a_1^2 t^2 + a_2^2 r^2) + (a_1^2 r^2 + a_2^2 t^2) \\ &= (t^2 + r^2)(a_1^2 + a_2^2) = (a_1^2 + a_2^2); \text{ for loss-less beam splitter} \end{aligned} \quad (9)$$

From the standpoint of classical physics, the π phase shift for all *external reflection* is of critical significance behind the capability of a beam combiner to re-direct energy from one beam to the other. In fact, a homogeneous boundary layer always behaves like an “active anisotropic” layer because the boundary layer molecules are constrained to oscillate more easily as dipoles along the plane of the boundary, than orthogonal to the boundary, when an incident oscillating electric vector stimulates them. This is at the root of Brewster’s Law, Malus’s law, and partial polarization of “unpolarized” light in reflection. EM waves always stimulate the material dipoles to oscillate along the direction of its E-vector, while the wave propagates through any medium [17].

The π -phase shift in the external “reflection” (see the sketch for the BC in **Figure 2**, thick line from the bottom on the BC) means that the surface dipoles are oscillating in such a way as to allow only π -shifted light to be reflected compared to the incident beam. If a collinear “transmission” beam (**Figure 2**, thin line from the left on the BC) wants to pass through in the direction of the external reflection (to the right), it has to match this π -phase shift. However, if the phase of this left coming “transmission” beam happens to be zero or modulo- 2π , its attempted dipole oscillation will be opposed by the “reflection” beam. The two incident amplitudes are now competing with each other in opposite directions. If the two amplitudes are equal, but opposite in phase, then all the energy of the two beams will be redirected along the upward direction, as *this direction provides an in-phase path for both the beams* and vice versa for the other direction.

The key point is that all beam combiners in all two-beam interferometers function this way when the Poynting vectors for the output beams are set for perfect collinearity and spatial coincidence. *The simultaneous physical presence of both the interfering beams from the opposite sides is must for the superposition effect to become manifest.* In other words, even if light consisted of “indivisible single photons,” we must have the simultaneous presence of two photons from the opposite sides of the beam combiner. Hence, if “indivisible photons” were the reality, then such a classical interference effect would not have been observable with the incidence of truly “one photon at a time.” The experiment we have presented used a 5-mW He-Ne beam, not “single photons.” Such an experiment is being carried out in many senior level physics/optics laboratories.

The following challenge unequal-beam-energy experiment which is yet to be carried out. The superposition conditions can be dramatized even further. Even if one uses a beam combiner with $r^2 \neq t^2$ (the energy must be conservation rule is preserved, $r^2 + t^2 = 1$), one can then alter the incident energies a_1^2 and a_2^2 proportionately to completely suppress the energy propagation in *one of the two chosen direction* under the relative π -phase shift condition for that particular direction. *Would one be able to explain such an unequal-beam-energy experiment using the model of “indivisible single photon interference”?* Remember, the mathematical model consisting of the equations given above corroborates the measured data. Note that this generic mathematical model requires the *simultaneous* presence of the two signals from the two opposite sides on the beam combiner incident with the *right phases* and *right amplitudes*. Then only they can create the desirable transmission (or reflection) along either of the two output ports.

3. Re-deriving Einstein’s photoelectric “energy” equation out of superposition effect

So far, we have only made passing negative comments about Einstein’s 1905 of “indivisible light quanta” without presenting a better model to understand the interaction processes behind the photoelectron emission. In this section, we “derive” the photoelectric *energy* equation using the inevitable superposition of amplitudes of multiple wave groups. As before, we are following semi-classical model for light-matter interactions.

Classical thermal radiation consists of random wave groups emitted spontaneously with random phases. They keep propagating while diverging out due to waves’ intrinsic diffraction property. The total dipolar amplitude stimulation of a bound electron can be expressed as:

$$\Psi = \sum_q \psi_q = \sum_q \chi(\nu_q) E(\nu_q) \quad (10)$$

The electron binding system must absorb the necessary $h\nu$ quantum-cup-filling energy, before the electron can be released to the conduction band, or become a free-space electron. This is a quadratic process:

$$|\Psi|^2 = \left| \sum_q \chi(\nu_q) E(\nu_q) \right|^2 \propto h\nu_q \quad (11)$$

We need to collect an *ensemble* of data to validate any characteristic behavior of a physical system. A single event (data point) is not sufficient to verify a theory.

$$\langle |\Psi|^2 \rangle = \left\langle \left| \sum_q \chi(\nu_q) E(\nu_q) \right|^2 \right\rangle \Leftrightarrow \langle h\nu_q \rangle = \langle \phi_{work\ fn.} + (1/2)m v_{el.}^2 \rangle \quad (12)$$

Note that we have “recovered” Einstein’s photoelectric *energy equation* out of dipole amplitude stimulations due to multitudes of waves. The left curve in Figure 3 was already published for Einstein to read [18]. His brilliance was to correlate the “minimum frequency” below which no photoelectron emitted to a unique “quantumness” in the phenomenon. He assigned this “quantumness” to “indivisible light quanta” in 1905 (“photon” word was coined in 1925 by G. N. Lewis). This was a brilliant idea at that time because even Bohr atom model with quantum mechanically bound electron was published 8 years later in 1913. However, *had Einstein correctly assigned the quantumness to bound electrons, he would have formulated*

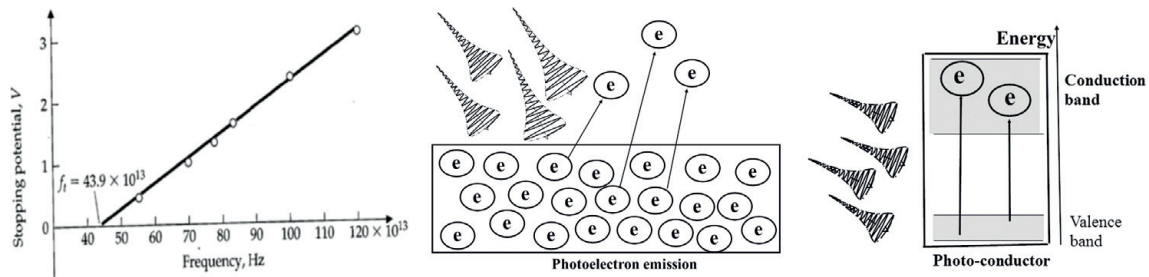


Figure 3.

Left diagram: Emission of photo electrons from a given material stops at a fixed specific frequency [18]. Middle diagram: Photoelectron emission from photo-cathode. Right diagram: Photoelectron transfer from valence to conduction band.

mathematics of quantum mechanics in his own style some 20 years earlier. Unfortunately, this neglect of the physical importance of amplitude stimulations as the critical first physical step before any quantum transition (energy exchange) can take place continued even after the QM was developed in 1925 and formalized during the next 10 years. We are stuck with the fictitious “indivisible light quanta” and “single photon interference.” It would be a great cultural anthropological study to analyze and understand why the absolute majority *bend over backward* to justify Einstein’s mistaken postulate, even though we now know that all electrons are bound quantum mechanically in materials. Recall the third line of Eq. (3). Waves only fill up the quantum cups with the necessary energy if the dipoles are resonant to the frequency ν of the incident waves (see left-diagram in **Figure 3**).

Let us rewrite Eq. (12) under the assumption that incident light is coming from a single frequency laser. In that case, $\chi(\nu_q)$ can be considered to be a constant and can be taken out of the summation sign:

$$|\psi_{res.}|^2 = \left| \sum_q \chi(\nu_q) E(\nu_q) \right|^2 = \chi^2 \left| \sum_q E(\nu_q) \right|^2 \quad (13)$$

The last step in Eq. (13) is meant to underscore again how some human invented mathematical logic, while corroborate measured data numbers can misguide us to believe that waves by themselves can carry out the complex operations of first (i) summing the wave amplitudes, and then (ii) taking square modulus of the sum.

4. Why we have been neglecting the obvious noninteraction of waves (NIW)

In both Sections 2 and 3, we have underscored the significance of noninteraction of waves (NIW). The neglect of NIW made us culturally oblivious to the fact that the *linear mathematical* superposition principle (SP) is not an observable phenomenon of nature. It *does not embody any interaction exchange process followed by nature*. In contrast, the superposition effect (SE) is an observable phenomenon because it models light-matter interaction process through the *nonlinear quadratic operation* $\psi^* \psi$. Note further that SE becomes manifest only in material detectors when their frequency resonant property matches with the frequency of the incident wave. NIW was known at least about 1000 years back [2]. It was repeatedly re-discovered but was neglected [10]. The puzzling issue is that this NIW is mathematically built into Huygens-Fresnel diffraction integral. Many modern undergraduate texts show constructions of Huygens’ secondary wavelets, evolving through each other unperturbed, to model diffraction, reflection, and refraction, while propagating through linear and anisotropic media [17]. Yet, current books and literature never

mention NIW. However, they present the linear superposition principle as the summation of wave amplitudes as if they physically sum themselves even while explaining that all propagation of light involves stimulating the dipoles of the material media. Note that the physical summation of wave amplitudes of different frequencies is behind the derivation of “group velocity,” which is not an allowed physical process of nature. Because of the flexibility in interpreting math, our time-integrated data gathering practice, etc., many of the data validate the mathematical model. This is how we have *learned to accept* SP as an observable phenomenon by itself through years’ of training. In the process, we have learned to suppress our inherent enquiring minds regarding the obvious contradictions while explaining many optical phenomena (see Ch. 1 in Ref. [1]). How have we acquired this culture of deferring to math and data without enquiring about the *physical interaction processes*? It took a series of grand mathematical successes in physics, during late 1800s and early 1900s, provided by only math and data, which is now known as the “evidence-based science.” Evidence-based (experimental) science is the best possible approach to generate objective information about natural phenomena. In addition, mathematics is the best possible logical and objective tool, so far invented by humans, to model nature. Unfortunately, neither of them separately, or jointly, can provide us with the complete information about any interaction in nature that we study. We have learned to ignore the fact that, albeit math being the best objective logical language to model nature’s behavior; it is just another human-invented language. Further, causal (or objective) mathematical equations require interpretations by human subjective minds. Math does not represent logical language that nature is obligated to follow. We have also learned to over-ride the fact that evidences (experimental data) still suffer from: (i) competing interpretations of data assigned by different subjective human neural networks, which have actually evolved for biological survival and not for the objective determination of the rules behind the biospheric and the cosmo-spheric evolutions. (ii) Further, no finite set of experimental data can provide us with the complete information about any natural entities. To be objective, we need to put careful and conscious efforts. Since the very beginning of biological evolution, our *pragmatic system engineering approach* to solve problems at hand with limited knowledge and trial-and-error has already made us the “top-dog” in the biosphere. We have installed the Global Internet System by figuring out the core system engineering functions for (i) generating, (ii) modulating, (iii) propagating, and (iv) detecting electrons and photons. However, we still do not understand what “photons” and “electrons” are made of. The lesson-to-be-learned is that a system engineering approach keeps us both grounded and pragmatically advancing. Whatever tools and technology works, they really obey the laws of nature even if we cannot articulate the rules.

Unfortunately, over the last century, we have deviated from consistently applying the system engineering approach to understand fundamental processes in nature [19]. This is evident from the broad cultural acceptance by the Knowledge Gatekeepers that the theories of Relativity and the mathematical formalism of Quantum Mechanics provide us with the final foundation of all future physics. Fortunately, the very long-term history of science does recognize that *all human constructed theories are necessarily incomplete since they have been formulated based upon insufficient knowledge of the universe.*

During the formative years of QM, people were marveled by the fact that Schrodinger’s $\psi^*\psi$ always gives the right result even though they could not give proper physical explanation regarding what ψ physically represents. Born explained it as the abstract mathematical “probability amplitude,” which must undergo an instantaneous “wave function collapse” to generate data in our instrument. This is certainly not a causal approach to understand and visualize the real physical

interaction processes in nature, which gives rise to observable physical transformations. This conceptual gap between ψ and $\psi^*\psi$ gave birth to the concept of “measurement problem,” which was then “solved” by using various elegant mathematical theorems. However, we have ignored the fact that if $\psi^*\psi$ gives us real world data, then ψ must also *contain* physical realities embedded in it. The author believes that ψ represents the real physical *amplitude stimulation* of the entity under study, as presented here in Sections 2 and 3 (see Ch. 3 in Ref. [1]). The square modulus operation represents energy exchanging *interaction process* between the interactants and between the energy donor and the energy recipient, guided by a force of interaction. These data generating interaction processes take a finite time. The interactants must first find the interaction *compatibility* with each other guided by the force they are experiencing and then undergo the full stimulation before jointly executing the square modulus operation to exchange the quantum cupful of energy. Let us elaborate the logical steps behind this physical process (see Ch. 12 in [1]).

- i. *Data are physical transformations:* A properly designed instrument can register the anticipated data only when the measuring instrument receives the appropriate signal indicative of some physical transformation experienced by the chosen interactants.
- ii. *Physical transformation require energy exchange:* Data generating physical transformation can happen only when the interactants exchange the necessary energy.
- iii. *Some force of interaction guides the energy exchange:* Only an allowed force of interaction, compatible with the interactants, can guide energy exchange toward some physical transformation.
- iv. *All “consumed” interactions are necessarily local:* Since all forces are of finite spatial range, the interactants must be physically present within this range of the guiding force. Thus, all interactions are “local” for the interactants as they must be within each other’s vicinity to experience the mutual force, which “dies out” with distance. This implicates that interacting particles cannot remain “entangled” beyond the range of the effective force of interaction (in the sense of continued *mutually influencing* remote interaction). Nature is strictly causal, not mystical. There is no interaction free superposition effect.

The purpose of Physics is to figure out the invisible interaction processes that

- i. *generate the data:* Our evolution and survival in the biosphere demand of us to think like system engineers and learn to manage the complex biospheric system. Unfortunately, we are not teaching our younger generation the extreme importance of understanding the depth of interaction processes going on in nature.
- ii. *The information retrieval problem:* We can now appreciate that the validation of a theoretical model for any specific interaction by some experimentally measured data does not help us visualize the microscopic interaction processes that generated the data. This is an eternal “Information Retrieval Problem” for humans. This is not a “Measurement Problem” that can be solved by further refinement of the instrument or by inventing some elegant mathematical theorem. Nature is a creative system engineer. From this

standpoint, we must figure out how to understand the details of the interaction processes. Today, we are facing the challenge of geoengineering the biosphere to slowdown the oncoming global warming. This is a formidable system-engineering task. Unfortunately, the physicists cannot contribute in this urgent process unless they are trained to enquire and understand the invisible interaction processes as system engineers.

- iii. *How we can attempt to visualize the invisible interaction processes:* First, we need to change our culture to accept explicitly that “evidence based science” will always represent incomplete science. Only our consistent enquiry in understanding the interaction processes will allow us to start getting closer and closer to understand nature’s system engineering marvels at both the micro and the macro levels. At present, we are happy with the Measurable Data Modeling Epistemology or MDM-E. MDM-E has successfully guided us to the highly advanced state we are in today. The author is proposing that we add Interaction Process Mapping Epistemology, or IPM-E, in conjunction with the prevailing MDM-E and accelerate our deeper understanding of nature as creative system engineers. Since the deeper realms and reality of nature are not directly visible to us, we will have to keep on applying IPM-E iteratively, perhaps, indefinitely. The progress will be slow, but we certainly will not fall in blind love with theories that are validated by data, but nonetheless do not represent nature’s actual working rules. Slowly, we will become efficient and conscious sustainer of the biosphere, instead of continuing to be the plunderers. Declaring war against the evolutionary behavior of nature (outcomes of the laws of nature) will be futile until we master the extremely complex system engineering rules of the biosphere. This is why we must teach the students to keep on challenging the foundational postulates behind all working theories and assure consistent evolution in scientific theories. Sections 2 and 3 of this paper represent out of measurable data for superposition effects.

Let us recall Newton’s philosophical view toward the end of his life: “If I have seen further than other men, it is by standing on the shoulders of giants.” Since 1400 until today, we must have been accumulating new knowledge developed by many thousands of deep thinking scientists. Conceptually, we have built a pyramid of knowledge out of all these contributions. We should learn to climb to the apex of this pyramid to increase our knowledge horizon. We should not bow down our head out of “messiah complex” and reduce our knowledge horizon.

Einstein is known to have said: “.... After 50 years’ of brooding over the question of what are light quanta; I still do not understand it!” This is the sign of a truly honest enquiring mind of a scientist. In spite of receiving the Nobel Prize for his proposed concept of “indivisible light quanta,” he kept on questioning it due to causal inconsistencies. This public “questioning” attitude of Einstein has provided the author the strength to explore critically whether “indivisible light quanta” can really exist [20]!

5. Conclusions

Our key objective behind this chapter has been to re-introduce noninteraction of waves (NIW), which is a very important reality of nature in the field of interferometry. Since different “photon” amplitudes cannot interact even while co-propagating or cross propagating through each other, once spatially separate, *EM*

wave packets cannot keep on influencing each other remotely; in this causal sense, they cannot remain “entangled.” I leave it to the readers to make the necessary adjustments in their future thinking whether “single photon interference” truly represents the reality of nature [21, 22].

The readers should also note that the implication of the generic NIW-property of all waves is very significant in most of the branches of physics, some of which have been elaborated in my book [1]. I believe that incorporation of NIW in our analytical thought processes would help us develop deeper understanding of nature, besides guiding us to improve upon and/or invent many new instruments.

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