Chapter 8
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The Double-Slit & the Mach-Zehnder Interferometer: Re-visiting through Asymmetry

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ABSTRACT

It is generally believed that the "mystery" behind understanding Quantum Mechanics (QM) and the global drives to construct quantum computers using "Entanglement", can be understood from how the two-beam superposition effect (SE) emerges out of a 2-slit, and a Mach-Zehnder Interferometer (MZI). This chapter rehabilitates the classical analyses of these two superposition effects, while exploiting functional asymmetries, either deliberately introduced or intrinsic in the two-beam apparatuses. We are using mathematical formalism already well-established in *classical optics* since 1800's, but with the extra emphasis that any final data generation requires some real *physical interaction* between the detector and the two light signals simultaneously stimulating the detecting molecules. This critical step of *physical interaction process* is not explicitly underscored by either the classical or the quantum physics. However, the asymmetry, either in the propagation or in the interaction process, is utilized to bring out the contradictions with the QM interpretations. For the 2-slit system, we deliberately introduce asymmetry on one of the slits. For MZI, the asymmetry is already built into the classical reflection property of a typical beams splitter.

Keywords: Asymmetry; interferometer: quantum mechanics; mach-zehnder.

1. INTRODUCTION

During the late 1600's, there was a debate on the wave-particle-duality (WPD) between Newton (proponent of "corpuscular" model) and Huygens (proponent of "non-interacting secondary wavelets" model). It remained unresolved because, as Newton had put it, none of them understood the fundamental nature of light. Even today we are still grappling to bridge the gap between the quantized emission of energy from atoms and the propagation of this energy as classical Maxwellian wave amplitudes. However, Newton's superior fame preserved the

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"corpuscular" model alive during entire 1700 over that of Huygens wave concept, without much progress in optical physics and engineering.

Then in 1802, Newton's "corpuscular" model was successfully removed by Young's demonstration of the double-slit superposition effect due to two diffracted waves out of two slits in the far-field from the slits. The physical phase differences between the two wave-amplitudes, spread over the detection screen, followed the wave propagation rules. In 1817, Fresnel introduced the Huygens-Fresnel Diffraction Integral (HF-DI), leveraging Huygens principle of wave propagation as *superposition* of innumerable secondary spherical wavelets. Then, the 1876 publication of Maxwell's equations on Electromagnetism and his wave equation for light waves, provided the deeper physical explanations and mathematical reasoning behind Young's 2-slit superposition experiment and the correctness of the HF-DI. Optical physics and engineering are still thriving using these developments of the century of 1800, without controversies.

It was the knowledge of classical optical spectrometry and classical technologies to quantitatively measure the variations of optical radiation energy with frequency out of a Blackbody, which gave birth to the concept of wave-energy being exchanged by atoms and molecules in discrete "quantum". Planck's derivation of this relation as an analytical expression, required him to propose/accept this hypothesis, $\Delta E = h\nu$. However, Planck still believed that light always propagated diffractively as waves to maintain the equilibrium energy density within the Blackbody cavity [1]. In those days, the light energy meters were photographic plates or bolometers. Even though the photoelectric effect was known during the very late 1800, the technology of quantum photodetectors were not available widely until 1930's and later.

However, in 1905, to explain the origin of the frequency-threshold below which no photoelectrons are emitted, Einstein proposed a new model of light as "indivisible light quanta", without providing any replacement theory that gives better physics and can do away with the then prevailing optical diffraction integral and the perpetual velocity of light (Maxwell's wave equation). We believe that this is one of the key reasons as to why we see self-contradictory interpretations started creeping in the emerging field of quantum theories.

The next conceptual platform to introduce the self-contradictory interpretations of 2-slit or 2-beam superposition effect emerged when Schrodinger's introduced his "wave equation" in 1926 that particles are plane waves and Bohr insisted that QM is not a statistical theory, it represents the physics of a single particle. Einstein apparently lost this debate with Bohr. Perhaps, this is why people started believing that "single photon" interferes. The problem is very subtle. When Schrodinger's equation provides the quantized energy levels of a Hydrogen atom, they are for a "single hydrogen atom". However, we can verify (measure) the validity of this QM prediction only when we study a similarly prepared ensemble of many Hydrogen atoms. This is also built into the quantum formalism. The data for quantum measurements are always represented by the ensemble average $\langle \psi^* \psi \rangle$, not just a single interaction $\psi^* \psi$. This, in reality, is not at all different from the measurements in classical physics. We can construct two precise robotic cricket playing machines and program them to pitch the ball and hit the ball exactly the same way every time. We know that the ball will land within a small zone, but not precisely on the same spot. Unaccountable and invisible "background fluctuations" are always present whether it is a classical ball or quantum particle, even though the detailed nature of the affecting "background fluctuations" will be different for the classical ball and the quantum particle. The spread (distribution curve) will be smooth for a very large ensemble; and noisy for very small ensemble. Statistical outcomes bounded by the laws of nature are universal and they are essential for the diversity of outcomes, a key necessity for sustainable evolution.

In experimental superposition data, people always find smooth fringes when the flux of light is high. The fringes start becoming noisy as the flux starts to go down. At very low flux, one has to increase the exposure (photon counting) period longer and longer. Such observations are routinely used to justify "single photon interference". However, a closer investigation of the experimental registration process, the quantum dipole nature of the detecting elements, reveals that the energy absorption process is still semi-classical, a closely spaced quantum detectors are competing with each other for the arriving low flux energy and must wait for their turn via long-term exposure. [See Fig. 5 and the Section 3.4 in chapter XX of this book.]

In section 2, we briefly present our view that seeking symmetry and beauty in structuring mathematical theory are not the best criteria to model physical phenomena of real nature. That is the reason we are analyzing the two two-beam superposition effects from the viewpoint of asymmetry.

In Section 3, we will present the classical mathematical model for the 2-slit superposition effect [2]. We will deliberately introduce asymmetric properties on one of the two slits to resolve the belief that the ignorance of "which way", or "which slit" the photon went through, is not the cause for the emergence of the 2-slit fringes. Human ignorance does not influence rules of interactions between natural entities. The universe is always objective in its behavior. Human minds are subjective and variable. Therefore, rules of nature should not be determined by consensus opinion of a group of strong minded people.

Section 4 will present the classical analysis of a Mach-Zehnder Interferometer (MZI) and some experimental data [3] while recognizing the built-in asymmetry, a π-phase shift by the beam splitter, which was derived by Fresnel using the classical concept of differential boundary conditions at the boundary between two media.

Section 5 leverages the equations developed in sections 3 and 4, and presents the arguments that neither of these two amplitude superposition equations can logically be normalized to represent a "singe photon", such that one can argue that there was only a “single indivisible light quanta” in the entire superposition apparatus. The intention has been to promote the non-causal view that single photons interfere, or “photon interferes only with itself”. However, the built-in logics in the mathematical relations, containing the sum of two complex amplitude terms, correctly validates the measured data in every detail. The mathematical validity of the superposition of two independent physical signals, do not causally validate the belief that a single entity can cause the superposition effect without any interaction with a suitable detector.

2. PAYING ATTENTIONS TO ASYMMETRY IN MODELING NATURAL PHENOMENOA

Physical transformations are key to perpetual natural evolution. Observations and mathematical modeling of natural phenomena clearly underscore the suitability of symmetry in acquiring some stability by many systems. Liquid drops and planets show preponderance towards spherical symmetry. However, the galaxies in the cosmic system show varied disc-like structures, along with spiral wings for some. Perpetual evolution requires perpetual transformations. Therefore, real physical interaction processes in nature, which drive evolution, cannot be driven by the interacting entities seeking out some “forever” symmetry. Natural evolution is dialectical and dominantly cyclical. Stable outcome of all interactions eventually have to succumb to new instability and the new products seek out new transformations, for another period of stability. Our point is that to model natural phenomena, we should not be driven by the biased human desire to find the simplicity, elegance, beauty and perfect symmetry in structuring a successful mathematical theory. It should be driven by modeling the real physical *interaction processes* that generate the physical transformations. We need to understand the interaction processes to appreciate the emergent structures of the outcomes.

Sometimes deliberate introduction of asymmetry, or seeking out asymmetry, in our mathematical modeling and in our experiments, while visualizing the interaction processes in nature, could reveal deeper understanding behind the real physical interaction processes.

3. YOUNG’S DOUBLE SLIT

3.1 Differentiating Mathematical Statement of Superposition vs. Superposition Phenomenon (SP)

Let us start with the traditional symmetric representation of the double-slit diffraction pattern, while explicitly recognizing the role of the detector that generates the measurable data. Data can be generated only after a detector has interacted with the desired signals. This key point, or the *interaction principle*, is not underscored in physics books and literature. It is a standard practice to represent the superposition principle as a simple linear sum of the two amplitudes, such as, $\Psi = \psi_1 + \psi_2$. This mathematical statement is not an observable; it does not represent a phenomenon of nature. This is only a correct mathematical first step, using the symbol, "+", indicating that we want to *sum two amplitudes*. However, we need a physical entity to execute this sum, or the "+"-operation. We need an appropriate detector containing atomic or molecular dipoles, resonant to the frequency of the incident light beams. If we use a visible light sensing Si-detector, but send high frequency deep UV light, we would not find any fringes. Otherwise, the Superposition Effect (SE) will not be executed. This is why any practical mathematical representation must incorporate the *interaction parameter* for the detecting material. For detectors consisting of atoms/molecules, the parameter is the dipolar polarizability χ_n of multiple orders. [See Eq.4, 5 & 6 in the chapter xx in this book]. For low to moderate levels of light, the values of χ_n beyond χ_1 are usually negligible. Therefore, the Superposition Phenomenon (SP) of nature should be written as $\Psi = \chi_1(\psi_1 + \psi_2)$. As per classical and quantum physics, the *energy* transfer is represented by the square modulus operation. So, the detected signal would be $D = |\Psi|^2 = |\chi_1(\psi_1 + \psi_2)|^2$. Let us remember that light propagates as a flux of wave amplitude. Our cameras always require a finite *exposure time* to integrate and absorb the necessary amount of energy out of the propagating wave amplitudes. When we express the amplitudes of AC currents or light waves in complex representation, the square modulus math effectively integrates the gathered energy averaged over a couple of cycles [4].

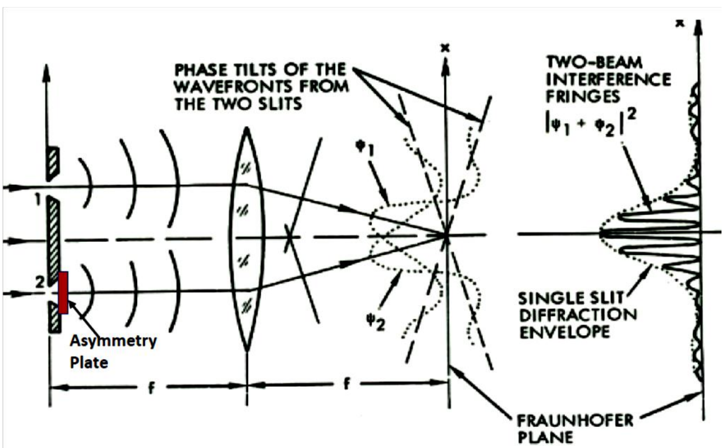


Fig. 1. How can one ascertain the reality of two signals in a double-slit experiment? The position of the lens with the symmetric focal-length spacing generates the far-field single-slit sinc-envelope with the standard cosine fringes underneath. The characteristics of the cosine fringes can be altered predictably while inserting asymmetry generating optical components (polarization, phase or amplitude) on one of the two slits

The cartoon in Fig. 1 represents a double-slit experimental setup with a lens of focal length f to simulate the far-field [5] and avoid the need for a very long table to reach the required far field condition necessary to obtain the classic cosine fringes under a common sinc-squared envelope generated by the two physically superposed single-slit diffraction patterns. When the two slits are identical in width $2a$, separated by $2b$, one can write the joint stimulating amplitudes $d(x)$ on a detector as [2,6]:

$$d(x) = \chi_1(\nu).2aE\mathrm{sinc}(2\pi ax/\lambda f)e^{i2\pi bx/\lambda f} + \chi_1(\nu).2aE\mathrm{sinc}(2\pi ax/\lambda f)e^{-i2\pi bx/\lambda f} \quad (1)$$

Then the time averaged energy registration can be given by:

$$|d(x)|^2 \equiv D(x) = B_1^2\chi_1^2(\nu)\mathrm{sinc}^2(\Lambda ax)\left[1+\cos(2\Lambda bx)\right]; B_1^2 \equiv 8a^2E^2 \ \&\ \Lambda \equiv 2\pi/\lambda f \quad (2)$$

Such cosine fringes, under a sinc-squared envelope, is shown in the right-side of the cartoon of Fig. 1. [In optical detection literature "detectivity" effectively keeps χ_1^2 absorbed in it.] Let us now introduce three different physical asymmetries between the two slits - polarization, phase and amplitude, by insertion of an appropriate polarizing plate, or a phase plate, or an optical absorption plate, in front of the slit #2 (Fig. 1). Symbolically, these properties can be accommodated by representing the electric amplitudes as a vector and an additional phase factor: $\vec{E}_1$ and $\vec{E}_2e^{i\varphi}$. The corresponding generic expression for the amplitude superposition is:

$$d(x) = \chi_1(\nu)2a\mathrm{sinc}(\Lambda ax)\left[\vec{E}_1e^{i\Lambda bx} + (\vec{E}_2e^{i\varphi})e^{-i\Lambda bx}\right] \quad (3)$$

Then the fringe energy distribution is:

$$\begin{aligned} D(x) &= \chi_1^2(\nu)4a^2\mathrm{sinc}^2(\Lambda ax)\left[E_1^2+E_2^2+2\vec{E}_1\cdot\vec{E}_2\cos(2\Lambda bx-\varphi)\right] \\ &= \chi_1^2(\nu)B^2\mathrm{sinc}^2(\Lambda ax)\left[1+\frac{2\vec{E}_1\cdot\vec{E}_2}{(E_1^2+E_2^2)}\cos(2\Lambda bx-\varphi)\right]; \text{where } B^2 \equiv 4a^2(E_1^2+E_2^2) \end{aligned} \quad (4)$$

We can now explore the effects of these three asymmetries, one at a time, to appreciate that the two signals emerging out of the two slits are physically real. Even if light consists of Einsteinian bullets, rather than Maxwellian time-finite wave packets [See also Ch.XX in this book], to accept *the causal reality of our experimentally validated mathematics*, we would need at least two "photons" simultaneously arriving at the same point on the detector to stimulate its dipoles, in-phase for constructive interference and, out-of-phase, for destructive interference. These are senior level laboratory experiments that are carried out in many institutions. An extreme reduction in the amplitudes of the incident light cannot invalidate the causal meaning of the two mathematical terms in Eq. 1.

3.2 Pure Polarization Asymmetry

For pure polarization asymmetry, we assume that the electric vectors are oscillating in different directions at an angle, but their projected cosine components still *jointly* stimulate the detecting molecule. This is classical Malus law. We are assuming that the two vectorial orientations are different but the amplitudes are equal: $|\vec{E}_1| = |\vec{E}_2|$. Then the double-slit energy distribution is given by Eq.5. Smooth rotation of the polarizer, will cause smooth variation in the cosine fringe contrast [5].

$$D(x)_{pol.asym.}(x) = \chi_1^2(\nu)B^2\text{sinc}^2(\Lambda ax)\left[1+\gamma_{po.as.}\cos(2\Lambda bx)\right];\gamma_{po.as.} \equiv \cos\theta, (\text{polarization angle}). \quad (5)$$

When the two electric vectors are exactly orthogonal, there will be no double-slit fringes. When the E-vectors are orthogonal, they cannot make the detecting linear dipoles oscillate in two orthogonal directions at the same time, at the high optical frequency. So the superposition effect cannot become manifest [2,7]. However, the presence of both the signals can be accounted for as the sum, or the doubling of the *two* single-slit, sinc-squared, intensity patterns, without the cosine fringes within. This is another way of validating the physical reality of the two light signals arriving, via classical diffraction process, on the detector and that it is the physical property of a detector that generates the observable superposition effect. The two mechanical *classical slits* are not introducing any “quantum magic” at the slit-plane.

3.3 Pure Phase Asymmetry

In case of pure phase asymmetry with $\vec{E}_1 = \vec{E}_2$, the Eq.4 simplifies to Eq.6:

$$D(x)_{ph.asym.}(x) = \chi_1^2(\nu)B^2\text{sinc}^2(\Lambda ax)\left[1+\cos(2\Lambda bx-\varphi)\right] \quad (6)$$

Effect of introducing the phase-asymmetry in the diffraction pattern due to a double slit is shown in Fig. 2, as a computer plot. However, such an experiment is very easy to carry out in the undergraduate lab. Introduction of a π/2-phase shift on the right slit, shifts the double-slit fringe pattern by one quarter of a fringe to the left. A π-phase shift makes the fringe system move to the left by half a fringe. Classical diffraction theory shows this reciprocal relation between the near-field and the far-field patterns. One can appreciate this reciprocal property of any far-field diffraction pattern from the space-space Fourier transform relation [5,6]. Such an experiment makes the reality of the two physically independent signals emanating out of the double-slit quite obvious. From this reciprocal asymmetry, we also know which slit is introducing the asymmetry.

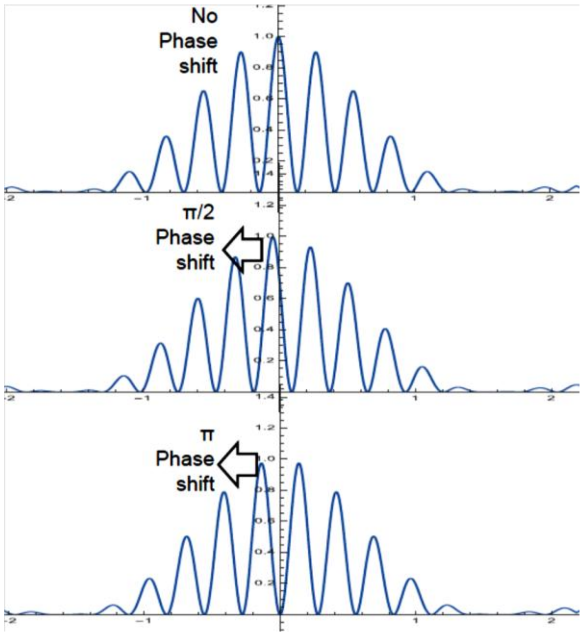


Fig. 2. Effect of introducing phase-asymmetry between the two-slit diffraction patterns. Introduction of a π/2-phase shift on the right-slit (slit#2 in Fig. 1), shifts the double-slit fringe pattern by one quarter of a fringe to the left. A π-phase shift makes the fringe system move to the left by half a fringe. This makes the reality of two physically independent signals emanating out of the double-slit obvious. We also know which slit is introducing the asymmetry [2]

This experiment can also decisively validate light from "which slit" is causing the fringe shift. Of course, we cannot precisely determine through "which slit" the classical light, or the quantum photon, had passed through. This is a silly question anyway. Light (or photon) cannot be detected without absorbing (destroying) them. Further, our working mathematical formalism does not allow us to ask this question, because only the square modulus operation on both the summed amplitude term create the detectable signal. We cannot detect the amplitudes of visible light, but we can radio or microwave frequency EM waves! Why is nobody spending research money to build quantum computers using microwaves and compact cellphone technologies?

3.4 Amplitude Asymmetry

From the second line of Eq.4, one can write the general purpose Eq.7, when $E_1 \neq E_2$, to analyze the characteristic changes in the fringe contrast, or the fringe visibility [8]. This is a fundamental concept in learning classical coherence theory.

Michelson introduced the definition of the fringe visibility in terms of maximum and minimum intensity distribution in the recorded fringes, $D_{\max}(x)$ and $D_{\min}(x)$, as $\gamma \equiv (D_{\max}(x) - D_{\min}(x)) / (D_{\max}(x) + D_{\min}(x))$ to invent his Fourier transform spectroscopy, which is now a major research and industrial tool for quantitative record of Raman spectrometry. Fringe visibility is also an integral part of classical coherence theory and a major tool for optical metrology using two-beam interferometry [9,10].

$$D(x)_{am.as.}(x) = \chi_1^2(\nu)B^2 \text{sinc}^2(\Lambda ax)\left[1+\gamma_{amp.as.}\cos(2\Lambda bx)\right]; \gamma_{amp.as.} \equiv \frac{2E_1E_2}{(E_1^2+E_2^2)} = \frac{2\beta}{\beta^2+1}; \beta \equiv \frac{E_1}{E_2} \tag{7}$$

Using this amplitude asymmetry, we now want to explore the “quantum mechanical assumption”, promoted by some that “photons do not arrive at the dark fringes”. In fact, this assumption is critical to over-ride the logics behind our successful mathematical relation that has two signals, but during the detection process only one signal, an “indivisible light quantum” determines where to arrive. From the first line of Eq.4, we can re-write it assuming only two different amplitudes (no phase shift or polarization):

$$D(x) = \chi^2(\nu)4a^2 \text{sinc}^2(\Lambda ax)\left[E_1^2 + E_2^2 + 2E_1 \cdot E_2 \cos 2\Lambda bx\right] \tag{8}$$

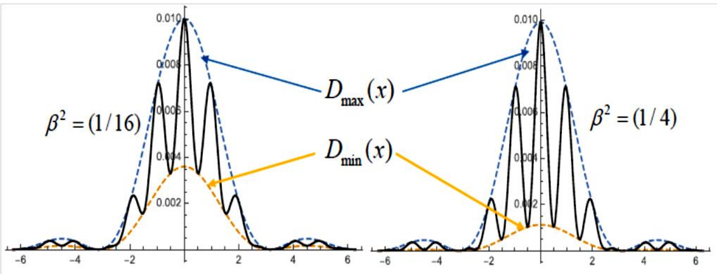


Fig. 3. The effect of amplitude asymmetry in a double-slit diffraction pattern. With unequal amplitudes passing through the two slits, the location of the fringe minima are no longer “zeros”. EM energy (“photons”) are registered at the locations of the fringe-minima because the unbalanced classical amplitude signal stimulates the local detector to absorb the proportionate amount of energy, as given by Eq.10 [2]

Then the envelopes of the fringe maxima and minima can be expressed as:

$$D_{\max}(x) = \chi^2(\nu)4a^2 \text{sinc}^2(\Lambda ax)\,[E_1 + E_2]^2 \tag{9}$$

$$D_{\min}(x) = \chi^2(\nu)4a^2 \text{sinc}^2(\Lambda ax)\,[E_1 - E_2]^2 \tag{10}$$

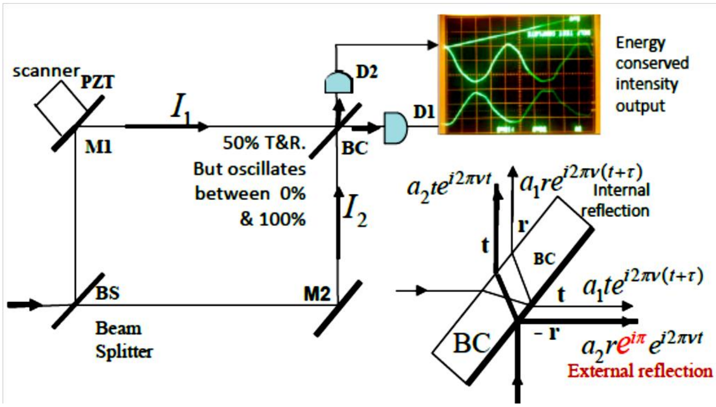
The envelopes of the maxima (upper dashed curves in Fig. 3), and the minima (lower dashed curves) are represented by Eq.9 and Eq.10, respectively. This fringe maxima and minima happen when the cosine factor in Eq.8 assumes the values “+1” or “-1”. Fig. 3 presents the computer plots for two different cases of intensity ratios, $\beta^2 \equiv (E_1 / E_2)^2 = (1/16) \& (1/4)$.

When the amplitude of the electric vectors at the detector-plane are exactly equal, $E_1 = E_2$, then $D_{\min}(x)$ envelope is always zero; see Eq.10. The out-of-phase and equal and opposite electric vectors cancel each other’s stimulation capability. Un-stimulated detector cannot absorb energy out of the two EM waves passing by them. The physical picture behind the interaction process is very clear, logical and robust. The stimulation is nulled; no energy can be absorbed. Does the alternate “quantum” interpretation of “non-arrival of photons” at $D_{\min}(x)$ locations is as robust as this semi-classical picture? The weakness of this “quantum” interpretation can be further appreciated, when one considers the asymmetric case, or when $E_1 \neq E_2$. Under this condition, the sinc-square envelope function is non-zero. Therefore, the $D_{\min}(x)$ has a definite vale across the interference pattern, representing the lower sinc-square envelopes, shown above. The physical processes behind the emergence of the double slit interference pattern is the physical superposition effect on a detector array of two single-slit sinc-amplitude diffraction patterns. All the mathematical expressions presented here are classical. They are experimentally validated since the first quarter of 1800. EM energy propagates as oscillating Maxwellian EM wave-amplitudes of the Ether, not as Einsteinian “energy bullets”. The presence of $D_{\min}(x)$ envelopes assures us that the locations of the fringe minima do experience diffracted EM wave passing by them.

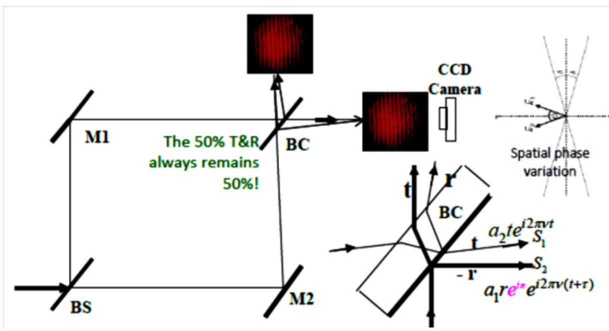
4. MACH-ZEHNDER INTERFEROMETER (MZI) WITH BUILT-IN ASYMMETRY IN ITS BEAM COMBINER

Material dipoles, respond to the E-vector of EM waves as dipole oscillators, whether individually, as in gas-phase, or collectively, as inside a bulk media or constrained by its boundary layer. These oscillations are guided by the E-vector, the B-vector and hence the Poynting vector (P-vector) of the wave front. Therefore, when the two beams are superposed on a beam combiner of an MZI to generate the Superposition Effect (SE), there would be two situations. The P-vectors of the two superposed beams can be collinear and coincident, or non-collinear and coincident on the beam combiner (BC) [see Fig. 4].

The asymmetry in an MZI arises out of π phase shift of the light beam undergoing the “external” reflection [7], from denser to the rarer medium, out of a glass surface to air. The magnified cartoons of the BC underscores this asymmetry in the Fig. 4 (a) and (b). The significance of this asymmetry, this π phase shift, will be discussed in the context of the equations Eq.11 and Eq.12.



(a)



(b)

Fig. 4. Two sketches of the two-beam MZI. (a) This sketch represents an MZI setup in scanning mode to generate fringes, where the two pairs of output beams emerge out of the beam-combiner BC with the Pointing vectors collinear, with the wave-fronts coincident. This is shown in the enlarged version of the BC. The two beams are also spatially coincident; but the rays on the enlarged BC is shown separate to provide the interaction details of the reflections and transmissions. (b) This sketch gives the details of the case when the MZI is aligned to generate spatial fringes with the Poynting vectors non-collinear, as shown on the enlarged sketch of the BC [3,7]

In modern days, with easily available lasers, interferometry is normally carried out by using laterally finite quasi-collimated Gaussian laser beams. For the case of two beams, collinear and coincident, as in Fig. 4 (a), the superposition effect, as re-direction of the two incident beams, is executed by the boundary layer of the BC (normally chosen as a 50/50 beam splitter, or $R = T = 0.5$, where R represents *intensity reflectance* and T represents *intensity transmittance*. For high frequency light beams, we can only measure intensities, not the amplitudes.

To underscore this point, we have used the symbols $I_{1or2}^{1/2}$ for the two amplitudes illuminating the BC and $R^{1/2}$ & $T^{1/2}$ for the amplitude reflectance and amplitude transmittance.

The generic mathematical expression for the up-going intensity and the right-going intensity due superposition of the two amplitudes and its square modulus to generate the intensity variations is given by the Eq.11, and Eq.12. The superposition of the two amplitudes are written within the symbol of square modulus.

$$\begin{aligned} D_{Up.}(\tau) &= \left| I_1^{1/2} R^{1/2} e^{i2\pi\nu(t+\tau)} + I_2^{1/2} T^{1/2} e^{i2\pi\nu t} \right|^2 = (I_1 R + I_2 T) + 2(I_1 I_2 TR)^{1/2} \cos 2\pi\nu\tau \\ &= A_{Up}^2 [1 + \gamma_{Up} \cos 2\pi\nu\tau]; \text{ with } A_{Up}^2 \equiv (I_1 R + I_2 T),\ \gamma_{Up} \equiv 2(I_1 I_2 TR)^{1/2} \big/ (I_1 R + I_2 T) \\ &= I[1 + \cos 2\pi\nu\tau]; \text{ only if } T = R = 0.5 \text{ and } I_1 = I_2 = I \end{aligned} \tag{11}$$

$$\begin{aligned} D_{Rt.}(\tau) &= \left| [I_1^{1/2} T^{1/2} e^{i2\pi\nu(t+\tau)} + I_2^{1/2} R^{1/2} e^{i\pi} e^{i2\pi\nu t}] \right|^2 = [(I_1 T + I_2 R) - 2(I_1 I_2 TR)^{1/2} \cos 2\pi\nu\tau] \\ &= A_{Rt.}^2 [1 - \gamma_{Rt.} \cos 2\pi\nu\tau]; \text{ with } A_{Rt.}^2 \equiv (I_1 T + I_2 R),\ \gamma_{Rt.} \equiv 2(I_1 I_2 TR)^{1/2} \big/ (I_1 T + I_2 R) \\ &= I[1 - \cos 2\pi\nu\tau]; \text{ only if } R = T = 0.5 \text{ and } I_1 = I_2 = I. \quad R + T = 1 \end{aligned} \tag{12}$$

The asymmetric π phase shift in “external” reflection has been incorporated as $\exp[i\pi]$. Classical electromagnetic theory has been developed as EM waves propagating as wave amplitudes, interacting with material dipoles as wave amplitudes, but transfer energy as square modulus. Later, QM formalism developed the reality that *material dipoles* have discrete *internal* energy levels and hence, for such internal energy level shifts, the energy exchange can happen only in discrete amounts of $h\nu$ through the ψ*ψ mathematical step, where ψ represents the initial amplitude stimulation, also like in classical optics. The bulk EM energy reflection, transmission, scattering, etc., follow continuous energy exchange process.

4.1 Poynting Vectors on the Beam Combiner are Collinear

For collimated waves with flat phase fronts on the BC, one can only observe a steady and fixed output energy in both the outputs, D1 (right-output) and D2 (up-output). This is because all the boundary layer dipoles are simultaneously responding to both the stimulating P-vector amplitudes and redirecting energy due to this superposition effect. To material dipoles, the multiple propagating wave fronts with collinear P-vectors, appear as a single stimulating EM wave. If the phase front is also uniform and flat, the entire surface of the BC will develop its effective reflectance and transmittance given by the Eq.11 and Eq.12, and reflect and transmit energy accordingly, without generating any fringes. To generate variable intensity fringes, one has to introduce relative phase variation on one of the two incident beams on the BC. This can be done by oscillating one of the two mirrors; here, it is M1as in Fig. 4 (a). The record of the two simultaneous outputs is shown on the top of Fig. 4(a), which is a snapshot of a dual beam oscilloscope record connected to the two detectors, D1 and D2.

Under the condition of collinear Pointing vectors and scanning mirror M1, the functional values of both $R \& T$ of the BC keep oscillating dynamically between zero and one, even though the designed values are fixed, $R = T = 0.5$. Thus, the π phase shift asymmetry tells us at any particular moment "which way" the optical beam energy is getting re-directed based on tracking the phase shift we introduce on the oscillating mirror M1, while using the classical Eq.11 & Eq.12. By blocking one of the two beams towards the BC, one will notice that the oscillatory nature of the outputs have been replaced by a steady DC out puts on both ports and the BC will behave as a normal beam splitter behavior of value $R = T = 0.5$, even if the mirror M1 keeps scanning. The *superposition effects can be generated by a boundary layer only when the two physical signals from the two opposite directions on the BC simultaneously interact with the entire boundary layer, which requires the collinearity of the Poynting vectors of the two incident beams on the BC.* By using a very low input intensity and a high amplification electronic photon counter for detection, we cannot claim that the natural phenomenon of superposition does not require the physical presence of two real physical signals from the opposite sides of the BC, even though our working mathematics says so. In fact, one can use various classical thermal detectors instead of a silicon photodetector to avoid confusion with quantum photoelectrons.

The conservation of total energy of the two incident beams on the BC can be easily appreciated from the two last lines of Eq.11 and Eq.12, due to the factor where we have assumed the two incident amplitudes are equal, $I_1^{1/2} = I_2^{1/2} = I^{1/2}$. Whenever the relative phase delay in the cosine term $2\pi\nu\tau$ assumes even or odd multiple of 2π, the last lines of Eq.11 and Eq.12 will always give zero in one direction and $2I$ in the other direction due to the factor $(1 \pm \cos 2\pi\nu\tau)$. This is shown in the oscilloscope picture on the top of Fig. 4(a) showing two cosine curves oscillating opposite to each other with the sum total energy remaining constant.

One can introduce further asymmetry in the two intensities, along with some conditional values for $R \& T$ such that $I_1 / I_2 = R / T$. This can allow one to generate fringes in the two outputs where one output displays perfect unit visibility fringes, while the other output will display lower than unit-visibility fringes. The maximum amount of energy.

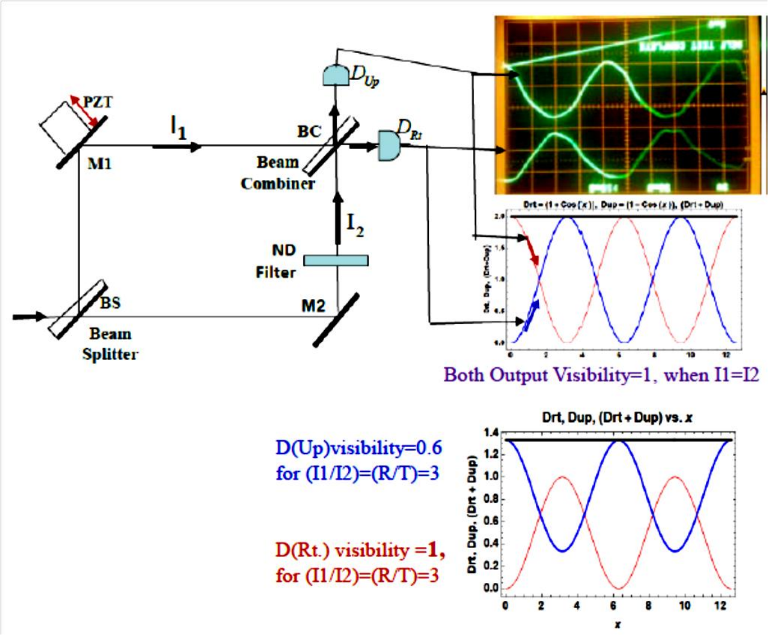


Fig. 5. Experimental and computed data for a scanning MZI with the output Poynting vectors collinear. The top-right photograph shows an oscilloscope display of the two simultaneous outputs received by the two detectors $D_{Up}(\tau)$ and $D_{Rt.}(\tau)$. The curves demonstrate the energy re-direction, while conserving the total energy, in the two ports as the phase of the left-arriving beam oscillates due to the scanning mirror M1; see the last lines of the Eq.11 and Eq.12. The computer oscillatory curves (blue for $D_{Rt.}(\tau)$ and red for $D_{Up}(\tau)$ demonstrates another asymmetry to determine "which way" light energy is coming and going while playing with the input intensities on the BC along with the complementary changes in its R and T values (see text for details) [3]

the BC can redirect in one direction, out of the other, is dictated by the lower-energy beam. Or, in other words, the question, "which way" the light energy is redirected due to the superposition effect can easily be determined by classical optical formalism. In the Fig. 5, the bottom pair of curves show the computer plot for the particular case when $I_1 / I_2 = R/T = 3$. Because $I_1 = 3I_2$, the unbalanced excess energy from the stronger left beam I_1 passes through the BC to the right output and reduces the fringe contrast (the blue curve). However, since $R = 3T$, the up-going two beam energies are equal, and hence the superposition effect give perfect visibility fringes. The top pair of computer output signals represent the earlier case, T=R=0.5 and $I_1 = I_2 = I$. For this case of perfect symmetry and equal division of both the beams energies in both the directions, one cannot discern which beam energy is going which way. Since most of the MZI entanglement experiments are carried out under this symmetric condition, it is easy think, at very low energy (photon count), that individual photons are either going up or to the right. They are never "split"! Unfortunately, nobody can directly count individual photons, because their energy is $\sim 10^{-18}\,Joules$. And our current optical energy meters can directly measure barely $\sim 10^{-12}\,Joules$ reproducibly and accurately. We count photoelectron *current pulses* (PCP) consisting of hundreds of millions of electrons, amplified some $\sim 10^{+9}$ times, or higher, through multistage complex electronic amplifiers, albeit starting with a single electron released by the action of many superposed random classical Maxwellian light pulses.

4.2 Poynting Vectors on the Beam Combiner are Noncollinear

When the Poynting vectors are non-collinear, as shown in Fig. 4 (b), the boundary layer dipoles oscillates separately to the tune of the two wave fronts, as if they are independently propagating signals. The superposition effect do not materialize on the boundary layer of the BC. The two pairs of output beams emerge at an angle to each other, as shown in Fig. 4(b). The plane wave fronts are at an angle to each other with spatial phase variations along the x-axis, as shown on the right-top sketch of Fig. 4(b). The emergent intensity of the two pairs of output beams will be dictated by the $R\,\&\,T$ values, as designed by the vendor. The corresponding spatial fringes, recorded by CCD cameras are shown as photographs on the top of the Fig. 4(b). To obtain the exact expression for the spatial fringes, one has to replace the τ in the phase factor $\exp[2\pi\nu(t+\tau)]$ by the appropriate spatial phase variation depending upon the tilt angle between the two emergent beams.

5. CAN WE NORMALIZE THE SUPERPOSITION EQUATION?

It is a standard practice in quantum mechanics to normalize sum of the two complex amplitudes factors in two-beam superposition equation by dividing both the complex amplitudes by $\sqrt{2}$ such that the square modulus of the sum represent the probabilistic cosine oscillation of the detected single photons [11-13]. Unfortunately, the real world two-beam superposition equation, stimulating a detector to generate data, are rather complex. Let us first recall Eq.13 for the double-slit superposition of two complex amplitudes, emerging out of the two slits and generating two single-slit "sinc"-amplitude-diffraction patterns with two extra phase factors based on the relative physical location of the two individual slits:

$$d(x) = \chi_1(\nu).2aE\mathrm{sinc}(2\pi ax/\lambda f)e^{i2\pi bx/\lambda f} + \chi_1(\nu).2aE\mathrm{sinc}(2\pi ax/\lambda f)e^{-i2\pi bx/\lambda f} \qquad (13)$$

Eq. 13 does represent real physical Superposition Phenomenon because it includes the data generating detector's amplitude-interaction (or, response) parameter, $\chi_1(\nu)$. This amplitude stimulation parameter $\chi_1(\nu)$ has a unique value for each specific detector. Once a detector is chosen, the value of $\chi_1(\nu)$ is fixed. It cannot be normalized to unity. Similarly, once the slit width $2a$ and the slit spacing $2b$ are chosen, the rest of the amplitude terms in Eq.1, including the spatially variable single-slit amplitude pattern, $\mathrm{sinc}(2\pi ax/\lambda f)$, also becomes determined; with unique numerical values and same with the two phase factors $\exp[\pm i2\pi bx/\lambda f]$. They cannot be arbitrarily normalized to fit the desired results afterwards.Let us now look at the pair of the two-beam amplitude-superposition equations, extracting them out of Eq.11 and eq.12.

$$d_{up}(t) = I_1^{1/2} R^{1/2} e^{i2\pi\nu(t+\tau)} + I_2^{1/2} T^{1/2} e^{i2\pi\nu t} \quad (14)$$

$$d_{Rt}(t) = I_1^{1/2} T^{1/2} e^{i2\pi\nu(t+\tau)} + I_2^{1/2} R^{1/2} e^{i\pi} e^{i2\pi\nu t} \quad (15)$$

Both the above two equations represent physical Superposition Phenomenon, since they include the light-matter interaction parameters $R^{1/2}$ & $T^{1/2}$. Clearly we do not have the logical authority to arbitrarily normalize $R^{1/2}$ & $T^{1/2}$, the values of which we normally request from a vendor to be 0.5. Further, the vendor will never promise to deliver a beam combiner whose approximate value of "0.5" will be accurate to the energy of a single photon, $\sim 10^{-18}\,Joules$! Our direct photon-energy measuring technology is still several orders of magnitude below $\sim 10^{-18}\,Joules$.

Our key point is that there is a fundamental difference between mathematical superposition principle and the Superposition Phenomenon (SP). The former is unobservable, and remains typed on papers as an excellent starting concept. The latter is observable and is generated by a real-world apparatus, leveraging the interaction parameter of a suitable detector. Once the detectors' unique interaction parameters are incorporated in the equation, along with other physical parameters, as in the case for the double slit, with the single slit sinc-diffraction pattern, etc., we must respect the causal mathematical relation already built-in. Forceful normalization will force us to search for non-causal explanation of the observed results.

Normalization in representing already gathered data for comprehensive presentation is a very valuable technique, while we preserve and keep track of the relative quantitative values with reference to the original data generated by our instruments. However, we must be very careful about arbitrary normalization procedures of specific physical parameters of natural entities. Normalization of intrinsic parameters of natural objects can distort the very physical meaning of the "working" equations. We have not yet developed the technologies to directly measure the energy of a single visible photon: $\tilde{}\ 10^{-18}$ *Joules*. We do not even know yet how to directly measure the amplitudes of visible light. Therefore, *we should be extremely careful before we start accepting mathematical theories that starts with pre-emptively normalizing the amplitudes of visible light.*

6. CONCLUSION AND COMMENTS

This chapter has used the classical mathematical formalisms to underscore its strengths in giving fully causal and rational explanations for the two most famous two-beam superposition apparatuses. We have deliberately incorporated asymmetries in the analysis to bring out the contradictions and non-causality built into the quantum mechanical interpretations of these two-beam interference effects. If the optical superposition phenomenon does become a different one at very low light level, we need to explicitly establish this and validate this with a proper physical theory and *causal* explanations, congruent with observations.

The classical and the quantum mechanical superposition principles are just mathematical statements of the simultaneous existence in the mathematical world of more than one signal whose sum can satisfy a specific linear differential equation as its allowed mathematical solutions. However, we believe that a real-world *Superposition Phenomenon* (SP) must have the potential to be observable or experimentally executable, where *all the potential signals* under consideration, should be able to trigger (induce) some form of amplitude stimulations simultaneously on a physically real detector. The detector to receive the stimulations, must have the appropriate *interaction parameter* suitable to respond to the stimulating signals. The *detector will then execute the square modulus operation* on its simultaneous stimulations and generate the data, which we call the Superposition Effect. The amount of the drawn energy will be dictated by the *intrinsic classical or quantum property of the detector*. However, the quantity of this energy would be proportional to the square modulus of *all the stimulating complex amplitudes*, not just one signal [14].

Young's demonstration of the double-slit experiment and its formulation in 1802 established the reality of light as EM waves, which was later formalized by a proper physical theory by Maxwell in 1876. Optical science and engineering has been flourishing continuously since Young's time without any serious controversy, unlike the interpretations of quantum formalisms. Accordingly, we should not abandon the more than a century old classical causal formalism and explanation in favor of the controversial interpretations proposed by QM of the same Superposition Phenomenon of nature. Quantum Mechanics has not yet developed a causal model to replace the "bullet photon" by the Maxwellian wave packet, which propagates as wave amplitude, leveraging the complex electromagnetic tension field of the free space, or of the material media (see also Ch.xx , 2022_BP_3810A 111).

COMPETING INTERESTS

Author has declared that no competing interests exist.

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