International Journal of Academic Pedagogical Research (IJAPR)
ISSN: 2643-9123
Vol. 10 Issue 4 April - 2026, Pages: 49-52

Teaching physics through experiments in interferometry with photons, particles and waves

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Abstract: *This article explores the use of interferometry experiments, focusing on the Mach-Zehnder interferometer, as a didactic tool for teaching fundamental concepts of quantum physics, such as wave-particle duality, superposition, and interference. Using the interactive simulation "Interferometer experiments with photons, particles and waves" from the University of St Andrews, we demonstrate how different models – classical particles, electromagnetic waves, and single photons – can be applied to describe the observed phenomena, facilitating the understanding of the distinctions between the classical and quantum views of nature. The comparative analysis of the simulated experimental results serves as a basis for in-depth conceptual discussions in the classroom, making quantum physics more accessible and intuitive for high school and university students.*

Keywords — interferometer; Mach-Zehnder; particles; teaching; experiment.

1. INTRODUCTION

Teaching Quantum Physics presents significant challenges, largely due to its counterintuitive nature and the abstract mathematics involved. Concepts such as wave-particle duality and the superposition principle challenge our classical perception of the world. In this context, the use of experiments, whether real or virtual, becomes an invaluable pedagogical tool. The double-slit experiment is historically the most cited example to illustrate the mysteries of quantum mechanics.

However, the Mach-Zehnder interferometer (MZI) offers a more versatile and conceptually clearer experimental platform to explore the same fundamental principles [1, 2].

This article aims to demonstrate how the analysis of an interferometry experiment, based on the interactive simulation "Interferometer experiments with photons, particles and waves" developed by the University of St Andrews, can be used as an effective teaching resource [3].

The simulation allows students to visualize and compare the behavior of classical particles, electromagnetic waves and single photons in the same experimental apparatus, highlighting the flaws in classical thinking and the need for a new paradigm: the quantum one.

2. METHODOLOGY

2.1 Wave-particle duality

Wave-particle duality is one of the pillars of quantum mechanics, postulating that all subatomic particles, such as photons and electrons, exhibit both particle properties (possessing localized momentum and position) and wave properties (exhibiting frequency, wavelength, and interference). This concept was proposed by Louis de Broglie in 1924 that associated a wavelength λ with any particle with linear momentum p.

$$\lambda = \frac{\mathrm{h}}{p} \qquad (1)$$

Where h is Planck's constant. Similarly, the energy E of a photon is related to its frequency f by the Planck-Einstein relation:

$$E = hf \qquad (2)$$

These two equations form the heart of wave-particle duality and were later confirmed by experiments such as the Davisson-Germer experiment [4].

In the context of the interferometer, duality manifests itself explicitly [5]. If we try to determine which path the particle followed (particle behavior), the interference pattern disappears. If we do not, the particle appears to pass through both paths simultaneously, like a wave, and interferes with itself. The simulation allows us to explore exactly this paradox.

2.2 The Mach-Zehnder Interferometer

The Mach-Zehnder interferometer is a device that splits a beam of light (or particles) into two and then recombines them. The basic configuration, as shown in the simulation, consists of a source that emits particles or waves, two 50/50 beam splitters: the first splits the beam into two paths and the second recombines them, two mirrors to direct the beams, a phase shifter in one of the paths to change the phase of the wave and two detectors at the output to measure the intensity.

2.3 Experiment via simulation

When configuring the simulation to emit classical particles, we observe that each particle follows one of two possible paths with 50.

When the source is tuned to an electromagnetic wave, the first beam splitter divides the wave into two. These two waves travel along different paths and recombine in the second beam splitter.

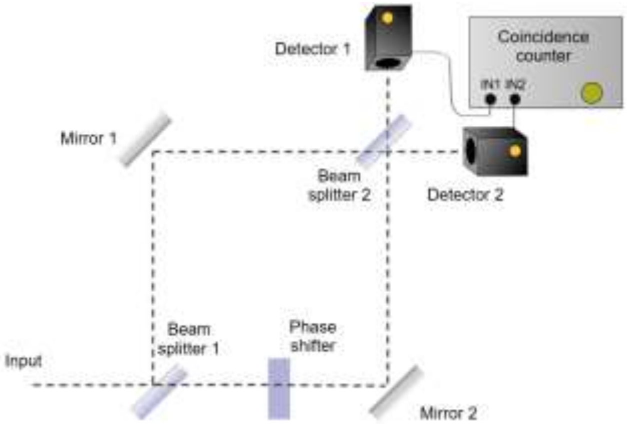


Fig 1. Schematic diagram of the Mach-Zehnder interferometer used in the University of St Andrews simulation.

The intensity at the detectors depends on the phase difference between the two waves. If the waves arrive in phase, constructive interference occurs at one detector and destructive interference at the other. If they arrive out of phase, the situation is reversed. The superposition of the waves at the second beam splitter leads to interference. The amplitude of the electric field at each detector, E_1 and E_2, can be written as the sum of the amplitudes of the two paths (upper, A_S, and lower, A_I). If the input amplitude is E_0, after the first beam splitter we have $A_S = A_I = E_0/\sqrt{2}$. Introducing a phase difference $\Delta\phi$ in the lower path, the amplitudes arriving at the second divider are A_S and $A_I e^{i\Delta\phi}$. The recombination results in:

$$E_1 = \frac{1}{\sqrt{2}}\left(A_S + iA_I e^{i\Delta\phi}\right) = \frac{E_0}{2}\left(1 + ie^{i\Delta\phi}\right) \qquad (3)$$

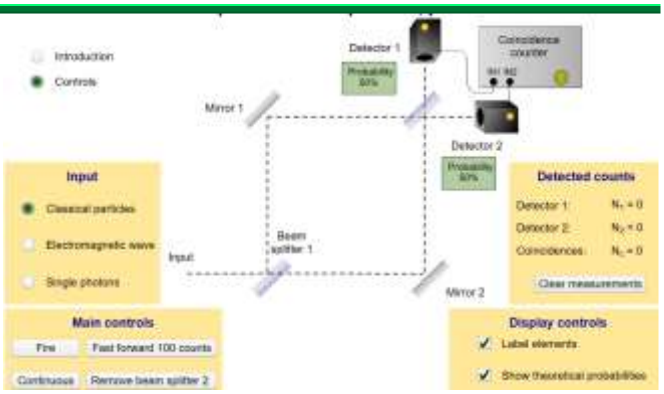
$$E_2 = \frac{1}{\sqrt{2}}\left(iA_S + A_I e^{i\Delta\phi}\right) = \frac{E_0}{2}\left(i + e^{i\Delta\phi}\right) \qquad (4)$$

The intensity, which is proportional to the square of the amplitude ($I \propto |E|^2$), in each detector will be:

$$I_1 = I_0 cos^2\left(\frac{\Delta\phi}{2}\right) \qquad (5)$$

$$I_2 = I_0 sin^2\left(\frac{\Delta\phi}{2}\right) \qquad (6)$$

Where I_0 is the total intensity. By varying the phase with the phase shifter, we observe the intensity in the detectors oscillating, a clear signature of wave interference.



Input
- ● Classical particles
- ○ Electromagnetic wave
- ○ Single photons

Detected counts

Detector 1: $N_1 = 0$
Detector 2: $N_2 = 0$
Coincidences: $N_c = 0$

✓ Label elements
✓ Show theoretical probabilities

Fig 2. Simulation result for classical particles. The detectors fire with equal probability, with no interference pattern.

2.4 Quantum Behavior: The Unique Photon

The most surprising result occurs when we send photons one at a time. Intuitively, we might expect that each photon, being a particle, would follow one path or another, as in the classical case. However, what is observed is that, even with a single photon in the apparatus at a time, the interference pattern gradually emerges as we collect data from many photons. The detection rate in each detector varies with the phase adjustment, exactly as in the case of the continuous wave.

This implies that the photon does not follow a defined path, but rather both paths simultaneously, in a state of superposition. The photon's wave function interferes with itself. The beam splitter does not "divide" the photon, but rather its probability amplitude. The probability of detecting the photon in one of the detectors is what shows the wave-like behavior. The quantum state of the photon $|\psi\rangle$, can be described as a superposition of the state corresponding to each path, $|C_S\rangle$ (upper path) and $|C_I\rangle$ (lower path) [6]. After the first beam splitters, the state is:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(i|C_S\rangle + i|C_I\rangle\right) \qquad (7)$$

The phase shifter introduces a factor $e^{i\Delta\phi}$ into the state $|C_I\rangle$. The probability of detection in each detector, P_1 and P_2, is the square of the projection of the final state onto the states of the detectors, resulting in the same $\cos^2$ and $\sin^2$ relations seen for classical waves.

3. RESULTS AND DISCUSSION

Figure 3 offers a powerful visual comparison between the three models (classical, wave, and quantum), allowing students to directly confront their classical intuitions with quantum predictions and observations.

The first three graphs are crucial for the initial discussion. Graph 1 (Classical Particles): Shows that the count in the detectors remains constant at around 50. Graphs 2 and 3 (Wave and Single Photon): In stark contrast, both exhibit perfect sinusoidal modulation. The count varies from 100.

These graphs delve deeper into the statistical analysis. Histograms (Graphs 4-6): The histogram for classical particles (4) shows a unimodal distribution centered at 50, reflecting random fluctuations around the mean. For waves (5) and photons (6), the distribution is bimodal, with peaks at 0 and 100. This means that, by varying the phase, the most probable states are those of totally constructive or destructive interference, a result impossible to explain classically for a particle.

Interference Patterns (Graphs 7-8): Graph 7 shows the continuous interference fringe pattern of a wave. Graph 8 is its quantum counterpart: individual points (photon detections) that, over time, build the same fringe pattern. This is perhaps the most direct visualization of duality: each detection is a particle event, but the collective distribution reveals the underlying wave nature.

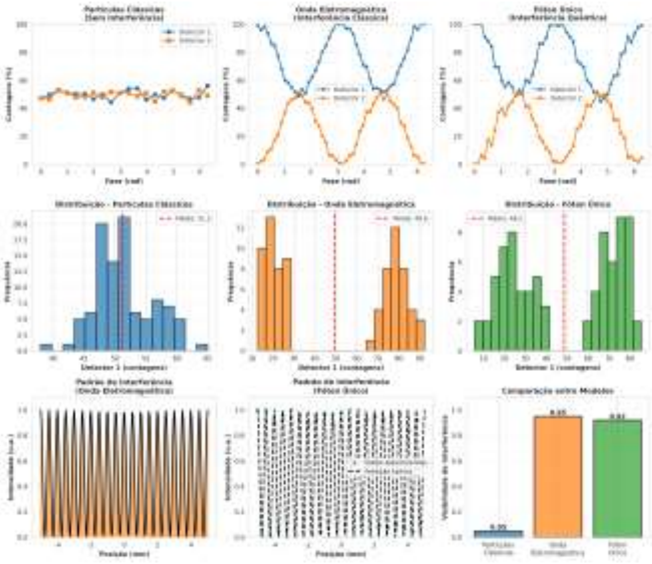


Fig 3. Collection of graphs generated from simulated data. (1-3) Counts in the detectors as a function of phase for each model. (4-6) Histograms of the distribution of counts. (7-8) Interference patterns for wave and photon. (9) Comparison of the visibility of interference between the models.

The concept of visibility ($V = \frac{\text{Imax}-\text{Imin}}{\text{Imax}+\text{Imin}}$) quantifies the contrast of the interference fringes. The bar graph (9) summarizes the discussion: the visibility for classical particles is close to zero (no interference), while for waves and photons it is close to 1 (perfect interference). This allows a quantitative and unequivocal conclusion: the photon behaves like a wave, not like a classical particle, in this experiment.

Figure 4 goes beyond physics and addresses the very process of scientific learning and investigation, modeling the types of results and analyses that students can perform.

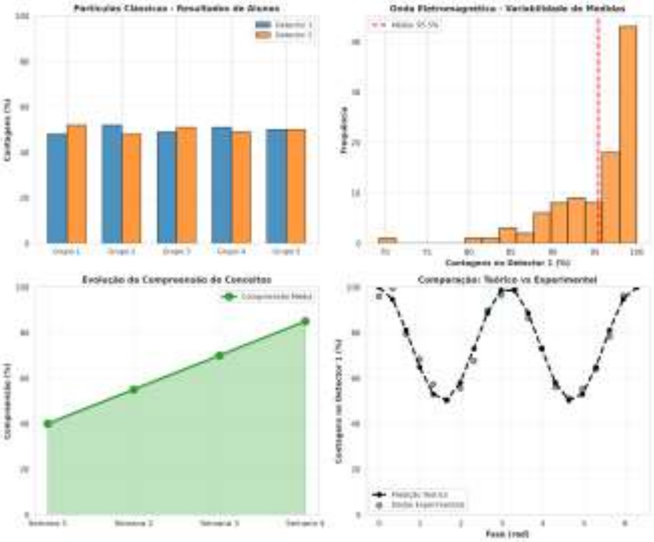


Fig 4. Graphs representing student results and progress. (1) Variability in results between different groups of students for the classical case. (2) Distribution of measurements for the wave case, showing experimental uncertainty. (3) Hypothetical learning curve. (4) Comparison between simulated experimental data and the theoretical prediction for the quantum case.

By integrating data collection and analysis, even if simulated, students cease to be passive spectators and become active participants in the construction of scientific knowledge [7]. They learn that physics is not just a set of equations, but a dynamic process of modeling, prediction and experimental verification.

4. FINAL CONSIDERATIONS

The Mach-Zehnder interferometer experiment, especially when explored through an interactive simulation like that of the University of St Andrews, serves as a powerful bridge between classical intuition and the revolutionary concepts of quantum mechanics. By allowing direct comparison between the behavior of individual particles, waves, and quanta, the simulation demystifies wave-particle duality and superposition, making them observable and debatable phenomena in the classroom. The incorporation of such tools into the teaching of modern physics is fundamental to preparing a new generation of students to understand the world from a quantum perspective.

5. REFERENCES

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