The Particle Illusion: A Closer Look at Feynman's Double-Slit Paradox

Terry Bollinger
2023-07-12.17:20 EDT Wed [Astrum addendum 2023-07-13] [Conclusion rewritten 2023-07-14]
https://youtu.be/og7UVNmVQqY&lc=UgyR_zmMozLx3X9ZG594AaABAg

A paper-length elaboration of a comment on the For the Love of Physics YouTube post:
Double Slit Exp & 5 MIND BLOWING Predictions about QUANTUM MECHANICS (Jul 3, 2023)
https://youtu.be/og7UVNmVQqY?t=0m3s

Abstract: In 1963, Richard Feynman gave a memorable lecture on quantum mechanics' strange and non-intuitive nature. Using the example of two-slit self-interference, he showed how quantum entities such as electrons appear to traverse two passages at once. While Feynman's analogy beautifully captures the strangeness of quantum behavior, it leaves open the definition of "particle." A few additions to his thought experiment provide another insight: Experimentally, the only definition of a particle possible is that it is a sequence of expanding quantum waves punctuated by minute exchanges of momentum and energy that relocalize and restart the wave. This article uses Dibyajyoti Das's beautifully done adaptation of Feynman's thought experiments to precisely assess what it takes to make an electron act like a bullet.

An Excellent Explanation of Feynman's Double-Slit Lecture

In 2023, Dibyajyoti Das produced a YouTube video (see [1]) on Richard Feynman's 1963 lecture [2] using paired slits to show just how odd quantum mechanics can be. Figure 1 shows Das's capture of Feynman cases of bullets, light, electrons, and observed electrons.

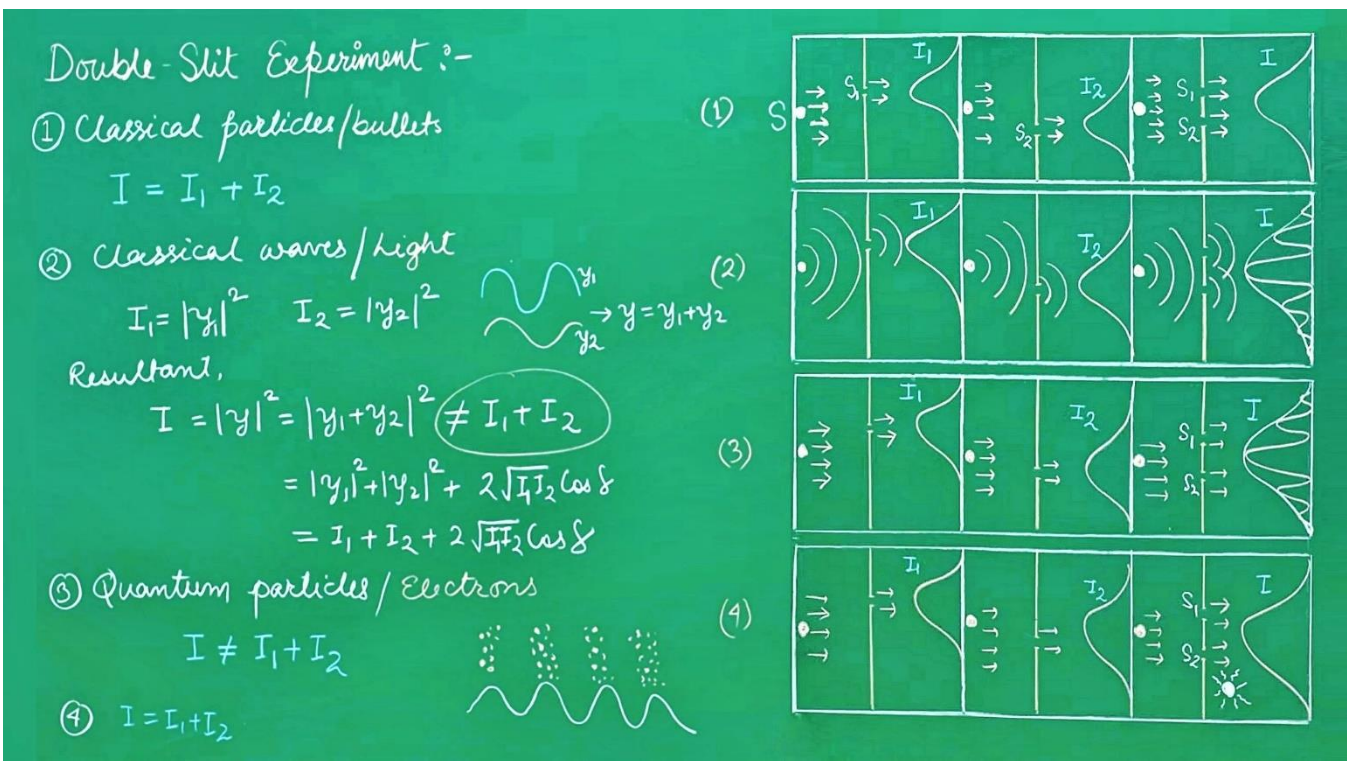

Figure 1. *Dibyajyoti Das's full blackboard shows the four cases of* (1) *bullets,* (2) *light,* (3) *electrons, and* (4) *observed electrons passing through one or two slits.*

Sand and Light, Hidden and Seen

Figure 2 shows the 2-slit cases. Note that this figure magnifies the distance between slits S_1 and S_2 by about 100 times, which is why they do not produce visibly doubled peaks. Case 1 shows bullets falling through slits, though sand grains give a more plausible scale. Case 2 shows the strikingly different *interference pattern* produced by light waves. The cause of this pattern is wave amplitudes adding or canceling depending on the ratios of the distances (number of wavelengths) the waves travel from each slit. Cases 1 and 2 represent the particle and wave behaviors of classical physics.

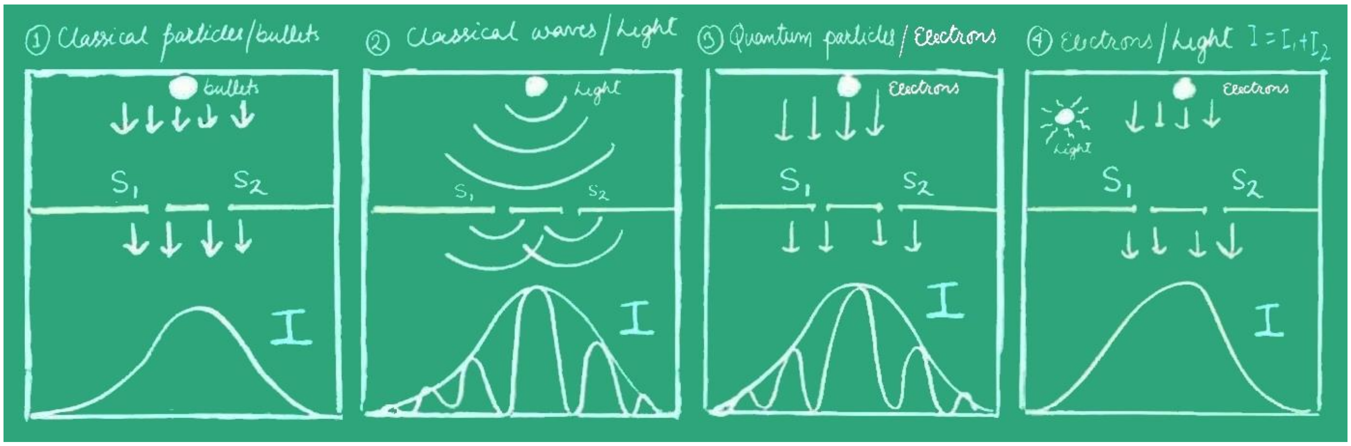

Figure 2. *Dibyajyoti Das's four Feynman-inspired cases of how* (1) *bullets,* (2) *light,* (3) *electrons, and* (4) *observed electrons land on a screen after traversing two slits. The slit separations are magnified about one hundred times compared to the fall patterns below. Note that this figure moves the Case 4 light to* above *the slits.*

Cases 3 and 4 represent quantum mechanics. The first surprise is Case 3, where electrons passing through the slits produce the same self-interference patterns as light waves. Louis de Broglie was the first to postulate this effect a century ago [3]. While counterintuitive, particle self-interference is well-documented not just for electrons but also for much larger entities. In recent years, teams have demonstrated double-slit interference patterns for large molecules with masses equivalent to about 2080 carbon atoms [4]. That is roughly the same mass as three DNA base pairs — three "letters" in a genome — and about 45.6 *million* times as massive as an electron.

Since wavelike self-interference flatly violates classical perceptions of how objects pass through openings, the first question most folks ask is: *Which way did the electron go?* Das addresses this question in Case 4 by shining a light on the slits S_1 or S_2 to see which one the electron uses. Notice, however, that in contrast to both Feynman's lecture (see Section 1-6 of [2]) and Das's blackboard, I've moved the light in Case 4 to a location *above* the slits, versus Feynman's and Das's placement of the light *below* the slits. Interestingly, this proves to be a critical difference; more later. The bright light, which Feynman places between the slits, reflects from the electron as it passes through one slit or the other and so appears to confirm our expectations that the electron (or molecule) travels through only one slit or the other. The problem is that the interference pattern disappears when you get the light bright enough to see which way the electron went! One can choose to know the electron's path or its interference pattern, but not *both*.

So far, so good: The inability to see the path and the interference pattern in the same experiment is the main point of both the Feynman and Das thought experiments. But why did I reposition the light *above* the slits? The change does not affect the outcome since the interference pattern disappears for either light position if the light is strong enough to spot the electrons. Feynman's placement of the light below and between the slits was one of experimental convenience since sensors on either side of the double slits could spot the distortion created by the electron immediately after it passed through the hole.

I moved the light to enable two additional experiments that address a question neither Feynman nor Das directly addressed: Once an electron passes through one or the other slit as a particle, does it *remain* a particle until it impacts the screen? Intuition says yes since all that is needed to discern the electron's path is to draw a line from the slit to the point where the electron impacts the screen. Images of charged particles racing through bubble detectors (Figure 3) confirm the correctness of drawing such extrapolations. One can easily find well-done YouTube presentations on the double-slit paradox that show just such straight paths for particles (photons, in that case) from the slit to the screen [5].

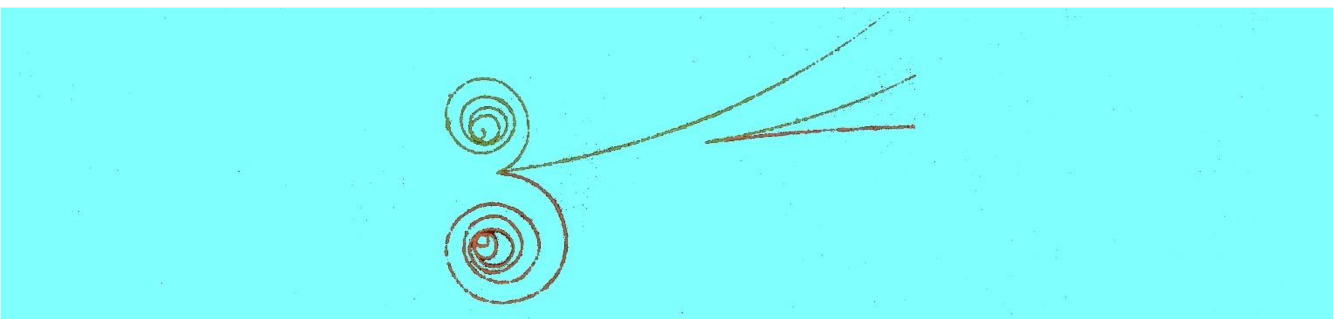

Figure 3. *Bubble chamber particle paths leave a powerful but incorrect impression that particles remain particle-like after initial detection or creation.*

The first step in exploring what happens to the electron between the slit and the screen is to add a new instrument to get more information. Figure 4 shows this modification, which consists of the experimenter replacing the original detection screen with a *diffraction lens* that redirects waves but not particles. A new detection screen resides at the bottom.

The purpose of the diffraction lenses is to attempt to refocus whatever arrives from the slits into an image of the slits, much like how a magnifying lens creates an image of ceiling lights in a room when held the proper distance over a flat surface. Successful imaging means that whatever fell on the diffraction lens was wavelike, and so could "see" the entire focusing structure of the diffraction lens. A failure to form an image means that whatever fell on the lens was particle-like and could only "see" the local structure of wherever it impacted the diffraction lens.

The first surprise when using the new apparatus is that the outcomes of Case 1 (bullets) and Case 4 (observed electrons) *no longer look similar*. The particle-like bullets could care less about the overall structure of the diffraction lens, and so and pass through the screen unaffected. In sharp contrast, the electrons passing through the dark chamber below the double slits now appear, if anything, *more* wavelike than before. They may, for example, form slightly sharper images of the double slits.

The implication is that the similarity of Case 1 and Case 4 outcomes in the original experiment was largely coincidental. Case 4 looks simple and smooth not because it used particles but because its *wavefront* was simpler, fading off slowly at its edges.

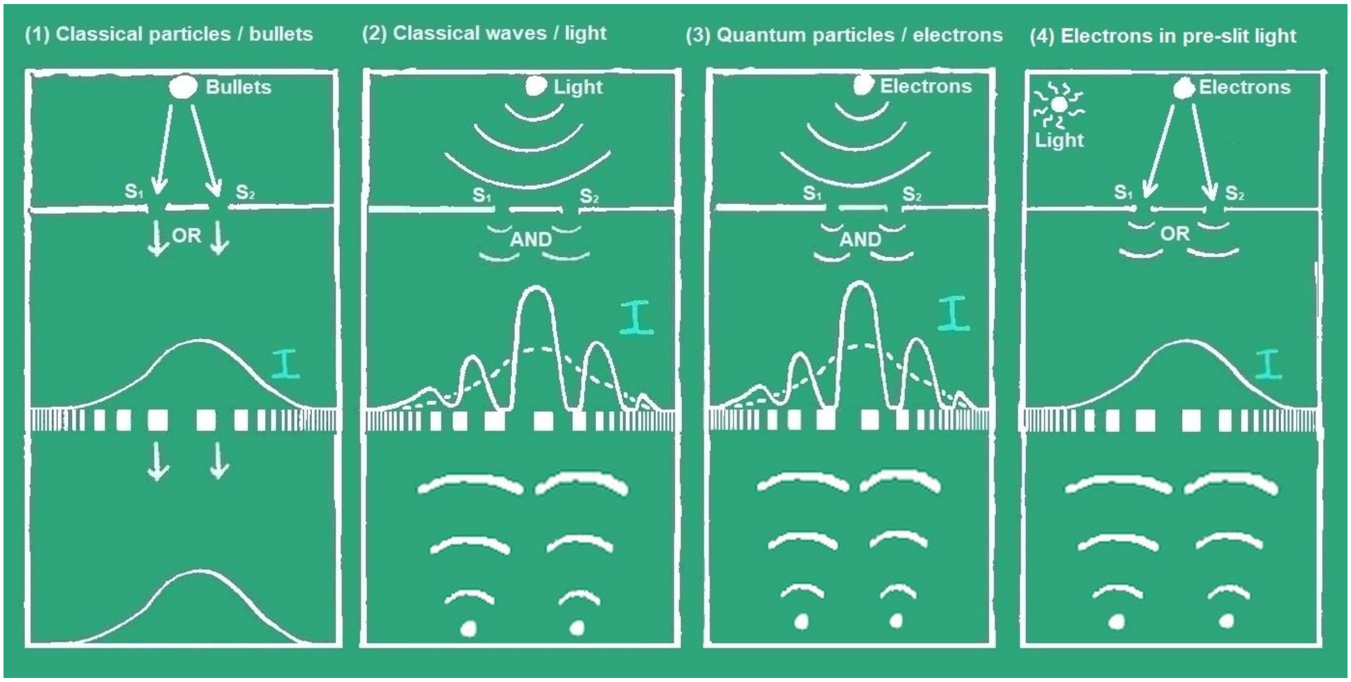

Figure 4. Replicating Figure 3 with a diffraction-grating focusing lens replacing the screen shows similarities between Case 1 and Case 2 to be an illusion. The grating does not affect the particle-like Case 1 bullets but refocuses the Case 4 electrons to produce slit images similar to those of Case 2 and Case 3. The implication is that the Case 4 interference pattern disappeared not because the electron followed a simple bullet-like trajectory to the screen but because it followed a wavelike path whose structure was simpler due to emanating from only *one* slit. Without dual exits, self-interference disappears, and the randomly alternating electron wavefront from S_1 and S_2 individually appear as simpler, smoother wavefronts whose intensities fade toward their edges. It is this edge fading that roughly mimics the spread of bullets.

The immediate return of particles to wavelike behavior when emanating from a small source is fundamental to quantum mechanics. In the decades before lasers, squeezing light through a small hole was the only method to create coherent light, with photons emerging as hemispherical waves on the other side of the hole. The situation is similar for electrons, which was hardly news to Feynman since the rapid return of found electrons to wavelike behavior is fundamental to his theory of quantum electrodynamics. In this lecture, however, he failed to emphasize such details, leaving the accidental impression that observed electrons remain bullet-like.

With this new ability to differentiate particle and wave results, it is now time to address the case of shining light on the electrons *after* the electrons pass through the double slits, which is the case both Feynman and Das use in their examples. Figure 5 shows how adding an intense light source to the lower chamber makes the electrons behave more like bullets. They again pass through only one of the slits but *stay* particle-like for the remainder of their journey to the lower detection screen. This time, the result is a profile that resembles the bullet case and is more than an accidental resemblance. They are indeed examples of similar physics.

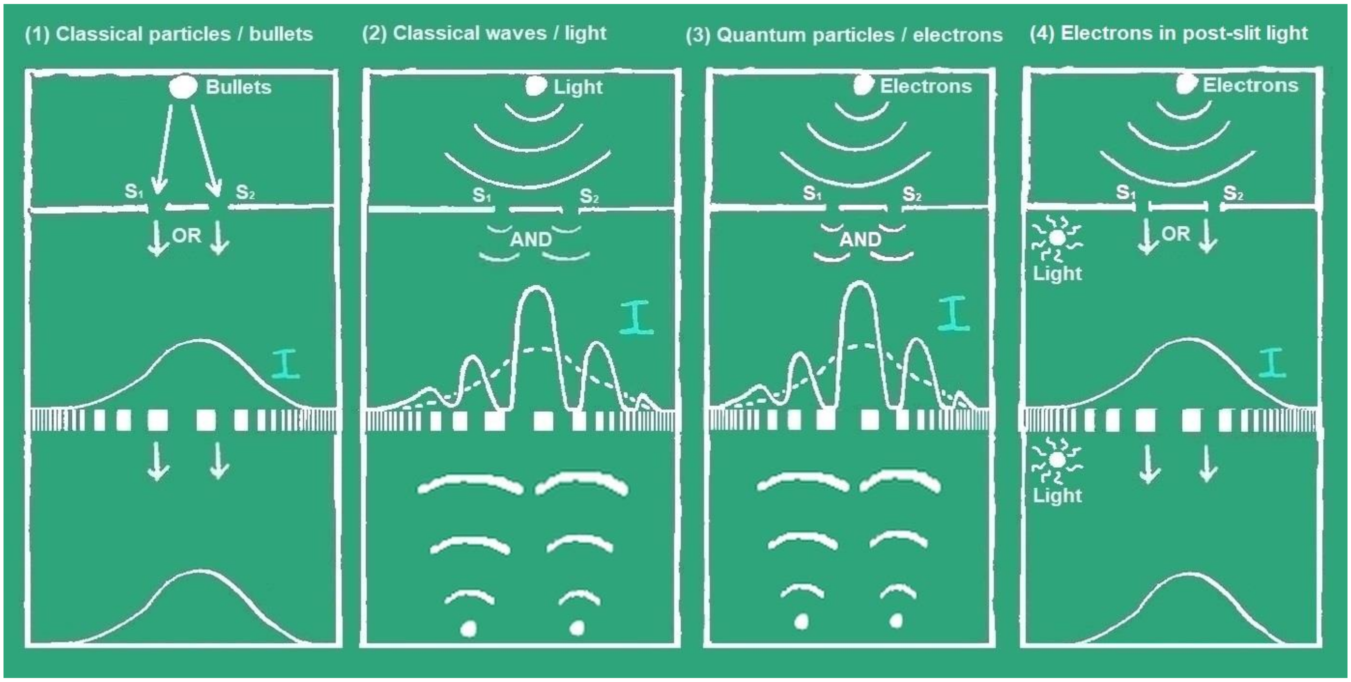

Figure 5. Repeating the Figure 4 experiment with the light *below* the two slits produces a Case 4 result that resembles Case 1 bullets more closely. As long as the light illuminating the electrons as they emerge from the slits is intense enough to track their motion almost continuously, the electron remains particle-like and, like the bullets in Case 1, unaffected by the diffraction lens.

A Recipe for Particle-Like Behavior

In many ways, this result is more unsettling than the previous return of the electrons to wavelike behavior. Why should *light* make electrons behave more like bullets? Figure 6 shows a magnified description of how intense light affects the electron wave.

The message of Figure 6 is not that electron wave behavior disappears but that repeated detections using light keep the wave behavior from spreading enough to result in effects such as two-slit diffraction. Unrelenting detection also makes electrons and positron paths in a bubble chamber (Figure 3) look fully bullet-like. In the case of bubble and cloud chambers, unrelenting interaction with observing bubbles or droplets has the same net result as the photon observation case. In contrast, any electron permitted to traverse large distances without incremental observations, as shown in Case 4 of Figure 4, follows wavelike mechanics.

Another critical point of Figure 6 is that *experimentally*, the concept of observation is neither complicated nor philosophical. If the electron bumps into something and exchanges a tiny bit of momentum and energy with it, *the electron is observed*. Any wavelike behavior must then restart from scratch. Neither the observed reduction nor the subsequence wave behavior is abstract since only the wavelike electron can engage in effects such as diffraction, reflection, and double-slit self-interference. Furthermore, reducing the number of detections also drops the number of path segments until an experimentally unique distinct mix of multi-scale quantum path segments emerges.

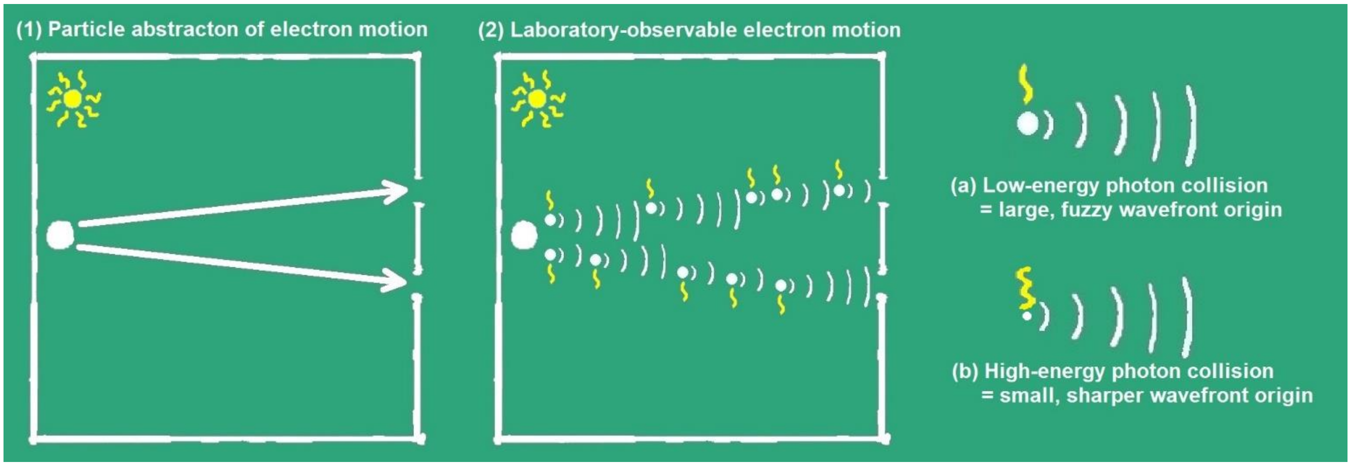

Figure 6. *There is no situation in which a bullet-like trajectory exists for any small particle traveling through a dark, empty vacuum. Closer examination shows every such path to be a concatenated series of always-expanding wavefronts linked by detection events that reset the wavefront to begin again from a smaller region of space. Each wave expansion supports experimentally detectable non-particle behaviors, including diffraction, reflection, and two-slit self-interference. The exceedingly brief periods in which the entity is spatially compact and thus "particle-like" are unstable and quickly convert into the next coherent wavefront in the journey. These compact regions always have finite volume due to the Planck volume-energy reciprocal relationship. For this reason, even particles such as electrons that lack discernable internal structure fail to become point-like at any energy level.*

The Illusion of Particles

When assessing odd data, it can be challenging to keep old assumptions from guiding us more than the data. An example is the century-old concept of particle-wave duality, in which deeply ingrained classical tendencies to interpret particles and waves as distinct phenomena drive us to interpret the world in terms of extrema that, at the experimental level, exist only as unreachable limits. A particle, for example, can never be more than an exceptionally closely-spaced sequence of quantum wave segments punctuated by minute but measurable interactions with its surrounding environment. High masses slow the dispersion of these waves but never prevent them from participating in non-classical phenomena such as two-slit self-interference. Thus what makes a bullet more particle-like is not its mass but its comparatively vast and highly interactive surface area. This large surface makes it a near certainty that the bullet continually exchanges exceedingly small units of momentum and energy with the innumerable atoms and particles surrounding it.

Finally, the more profound message is that since our definition of xyz space depends on, and is complementary to, the concept of "particles" moving "through" xyz space, that definition also cannot be fundamental. Space is a construct created by groupings of entities that continually reduce and limit each other's wave natures. Far from being unrelated to classical mechanics, the infamous "quantum collapse" of the Copenhagen interpretation is, instead, the founding principle behind the emergence of xyzt space.

References

[1] Dibyajyoti Das, *Double Slit Exp & 5 MIND BLOWING Predictions about QUANTUM MECHANICS*, For the Love of Physics, YouTube (Jul 3, 2023). https://youtu.be/og7UVNmVQqY&t=0m3s

[2] R. Feynman, *Quantum Behavior* [Lectures III, Chapter 1], The Feynman Lectures on Physics (1963). https://www.feynmanlectures.caltech.edu/III_01.html.
For Das Case 1, see Feynman Section 1–2, *An experiment with bullets*.
For Das Case 2, see Feynman Section 1–3, *An experiment with waves*.
For Das Case 3, see Feynman Section 1–4, *An experiment with electrons*.
For Das Case 4, see Feynman Section 1–6, *Watching the electrons*.

[3] L. de Broglie, *Waves and Quanta*, Nature **112**, 540 (1923). https://www.nature.com/articles/112540a0

[4] Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich, and M. Arndt, *Quantum Superposition of Molecules Beyond 25 kDa*, Nature Physics **15**, 1242 (2019). https://www.nature.com/articles/s41567-019-0663-9

[5] A. McColgan, *The Attribute of Light Science Still Can't Explain*, Astrum (2023-06-15). My analysis is at https://youtu.be/TfwaEhNg9Oc&lc=UgytFQi-y5vj0EnfwAx4AaABAg:

7:53 *"Scientists tried [to see if a photon passed] through both [slits] at the same time. It didn't."* Correct, but what you show happening next is wrong. After passing through one or the other slit, a photon is equally likely to land on *either* of the two far sensors. Photons don't travel in straight lines, ever.

If the slits are narrow enough to cause self-interference, they are necessarily narrow enough to cause significant light spreading through one slit. Otherwise, the wavefronts from the pair of slits would never overlap to form an interference pattern.

Maxwell's equations beautifully and precisely describe the spreading effect from one slit. For very-low light intensifies, these entirely classical equations become to massless photons what Schrödinger's equation is to massive particles: A precise description of an ever-expanding wave of probability.

As with Schrödinger's equation, such electromagnetic probability waves exhibit effects such as self-interference even when they become indefinitely vast. For example, Maxwell's equations, interpreted as probabilities, apply even to a photon passing through a cosmic Einstein lens millions of lightyears wide.

For a pinhole slit barely large enough for a single photon to pass, the photon wave becomes hemispherical on the far side of the hole. That means the photon could land anywhere with equal probability.

Thus the correct physics and animation for the case you show at 7:53 of photons passing individually through one or the other slit is for each photon to become a spreading wave that is *equally* likely to hit either of the two sensors shown.