FN-Quanten-Dualitas-EN-v0.1-2026-05-17

Research Note — Double Slit with Single Quanta

Author: Thomas Schüller · forschung@tschueller.com · ORCID 0009-0003-9799-6747 **Affiliation:** privately funded, no institutional affiliation **Licence:** CC BY 4.0 · **Version:** 0.1 · **Date:** 2026-05-17 **Strand:** FORSCHUNG / Quanten (Quantum) / Q1 Double Slit **Tool:** DUALITAS · **Document type:** Research note (Template v1.0) **Status:** completed test with documented assessment **Special feature: opens the quantum cluster**

---

1. Thesis

Two merge modules converged on the same point. In **M2 (ANALOGON)** the optical-mechanical analogy broke at the wavelength — de Broglie and Schrödinger took the break seriously and arrived at wave mechanics. In **M3 (OSCILLATIO)** the classical description broke at $\hbar$ — Einstein and Debye thereby solved the heat-capacity puzzle. Both times the break was the transition. Here it becomes the subject.

The tested baseline model M1 reads: *“A particle goes through one of the two slits. What arrives at the screen came either through A or through B; the pattern is the sum of both possibilities.”*

This module’s claim: M1 is false, demonstrably — the classical sum of two single slits does not reproduce the measured pattern. At the same time every single detection is a localised point. **Neither “particle” nor “wave” alone captures the finding.**

A delimitation up front, valid for this whole module: what is computed here are probabilities for measurement outcomes. What happens between source and screen is **not** in the formalism. Popular accounts introduce narratives there — “the particle knows”, “the observer decides” — that the calculation does not supply. The question of interpretation is the subject of the planned module W2 and remains expressly open here.

2. Assumptions

1. The source emits single quanta, separated in time.
2. Every detection is a localised event at one place.
3. Quantum mechanics supplies a probability density for the detection location.
4. Which-path information can be quantified as distinguishability D.
5. Visibility V is defined relative to the local envelope.

3. Mathematical model

M1 — "one path": The pattern is the sum of the single-slit distributions: $$P_{\text{class}}(x) = \tfrac{1}{2}\left[I_1(x) + I_2(x)\right].$$

M2 — quantum prediction. Amplitudes are added, not intensities: $$P(x) = \left|\psi_1(x)+\psi_2(x)\right|^2 = I_{\text{env}}(x)\,\frac{1+V\cos\delta(x)}{2}, \qquad \delta = \frac{2\pi d\,x}{\lambda L}.$$

M3 — complementarity (Englert 1996). For which-path information D and visibility V: $$V^2 + D^2 \le 1,$$ with equality for ideal measurement.

M4 — model comparison. For the same data the log-likelihood ratio is formed: $$\Delta = \sum_i \left[\log P(x_i) - \log P_{\text{class}}(x_i)\right].$$

Symbol	Meaning	Unit
d	slit separation	—
V	fringe visibility	—
D	path distinguishability	—
Δ	log-likelihood ratio	—

4. Parameters

Scenario	Setup
A single events	$d=6$, $a=1$; N from 1 to 100,000; 400 resp. 40 repetitions per stage
B complementarity	D from 0 to 1 in eight steps
C quantum eraser	visibility in the flat region $|x|<0.4$, envelope divided out

Tolerance: $\varepsilon = 0$ in A, 10^{-9} in B, 0.1 in C.

5. Prediction

Scenario	Expectation
A	no discrimination at small N; clear preference for the quantum prediction as N grows
B	$V^2+D^2 = 1$ across the whole range
C	subsets with full visibility, sum without fringes

6. Falsification criterion

M1 is refuted as soon as the classical sum describes the data significantly worse than the quantum prediction — measured by the log-likelihood ratio relative to its scatter.

7. Competing models

- **K1 — one path (M1):** tested baseline; corresponds to the classical particle picture.

- **K2 — pure wave description:** explains the pattern but not the localised single detections.
- **K3 — complementarity (Bohr):** wave and particle as mutually exclusive descriptions.
- **K4 — quantitative complementarity (Englert):** an inequality rather than a switch — sharper than K3.
- **K5 — interpretations:** Copenhagen, many-worlds, Bohm, GRW, QBism — they differ in the narrative, **not in the predictions**. Subject of W2.
- **K6 — decoherence:** explains why interference vanishes in macroscopic systems — but does not answer the interpretation question.

8. Domain of failure

- **Idealised setup.** Point source, monochromatic, no decoherence, perfect detectors. Real experiments contend with all of this.
- **Arbitrary units.** d, a, λ, L are chosen dimensionless; the calculation shows structure, not concrete fringe spacings.
- **The Englert relation is not derived** but used. Its derivation requires the full formalism.
- **The quantum eraser is not simulated dynamically.** The coincidence subsets are constructed from the known result, not from a two-particle calculation. This shows the structure correctly but does not replace an entanglement calculation.
- **No interpretation.** What happens between source and screen is expressly **not** the subject here. Whoever seeks an answer will not find it in this note — nor in the formalism.
- **No Bell test.** The question of local realism is a topic of its own (planned in the cluster).

9. Simulation

Numerical evaluation in `dualitas_simulation.py`:

1. Scenario A: drawing detection locations from the quantum prediction; log-likelihood of both models for the same data; mean and scatter over many repetitions.
2. Scenario B: Englert relation for eight values of D; test of equality.
3. Scenario C: visibility of the total pattern, the marked pattern and both subsets, each with the envelope divided out.

Results in `dualitas_results.json`, plot as `dualitas_szenen.svg`.

10. Result

10.1 A — single events

N	Δ (mean)	Scatter	S/N	conclusive
1	5.94	4.27	**1.39**	**no**
10	58.78	15.52	3.79	yes
100	586.77	46.23	12.69	yes
1,000	5,862.63	142.22	41.22	yes
10,000	58,649.72	408.17	143.69	yes
100,000	585,775.94	1,537.93	**380.89**	yes

Assessment M1: refuted.

10.2 B — complementarity

D	V	V^2+D^2
0.0	1.0000	1.000000
0.4	0.9165	1.000000
0.707	**0.7072**	**1.000000**
0.8	0.6000	1.000000
0.95	0.3122	1.000000
1.0	0.0000	1.000000

Assessment M1: refuted.

10.3 C — quantum eraser

Condition	Visibility
without which-path information	1.0000
with which-path information	**0.0000**
coincidence subset 1	1.0000
coincidence subset 2	1.0000
sum of both subsets	**0.0000**

Assessment M1: refuted.

11. Assessment

M1 (“a particle goes through one of the two slits”) is refuted in all three scenarios.

Scenario A shows both at once. Every single detection is a point — localised, at one place, not smeared. This is particle-like and leaves no room for interpretation: the detector clicks once, at one spot.

And yet the classical sum of two single slits does not reproduce the distribution of these points. The log-likelihood ratio grows linearly with the number of events; at 100,000 detections the signal-to-noise ratio is 381. The data prefer the quantum prediction not narrowly but overwhelmingly.

The lower bound matters. At **N = 1** the S/N is 1.39 — **no discrimination possible**. A single point fits both models; it may land by chance where the predictions diverge. Only from about ten events does the statement become conclusive. This is no weakness of the calculation but a factual property: **the interference pattern is a statement about ensembles, not about single quanta.** A single quantum does not visibly “interfere” — it lands at a place.

Scenario B replaces a switch with a balance. Bohr’s complementarity is often presented as an either-or: either wave or particle, depending on the apparatus. Englert’s relation $V^2+D^2 \le 1$ is more precise. The calculation confirms equality exactly across the whole range.

The intermediate region is decisive. At $D = V = 0.707$ one has **both at 71 %**: partial which-path information *and* partially visible fringes. There is no switching point. **The question is not “wave or particle” but: how much which-path information do I have, and how much interference then remains?** The answer is an inequality.

This strikes M1 directly: M1 presupposes full which-path information ($D = 1$) and would thereby force $V = 0$. But interference is measured — so the which-path information is not present.

Scenario C defuses a widespread misunderstanding. The quantum eraser is often told as if a later decision could change the past. The calculation shows what actually happens.

The two coincidence subsets each have full visibility (1.0), but they are shifted against each other by half a period. **Their sum has visibility exactly 0.0.** That is: **the total pattern at the screen never changes.** Whoever looks only at the screen always sees the same structureless image — whether the which-path information was erased or not.

The fringes appear only when one **sorts** the detections afterwards by the measurement result on the partner particle. This sorting information must be transmitted classically. **This is why nothing can be transmitted and nothing changed retroactively:** without the information on how to sort, the receiver sees only noise. The quantum eraser is not a channel into the past — it is a statement about which correlations are contained in the data.

What this module does not achieve — and why that matters. The three scenarios show what is predicted and measured. They do **not** show what happens between source and screen. This gap is no deficiency of the simulation but the state of affairs itself.

The formalism contains no narrative about the quantum's path. It supplies amplitudes from which probabilities follow. Sentences like "the particle goes through both slits", "it knows whether it is measured", "the observer collapses the wave function" are **interpretations** one adds — and different interpretations (Copenhagen, many-worlds, Bohm, GRW, QBism) make **the same predictions**. They are therefore not distinguishable by this experiment.

This continues a pattern running through the workshop. In **M1 (CATENA)** it emerged: the output of a measurement chain does not determine the stimulus uniquely. In the **perception strand**: we do not see the stimulus but the best interpretation. Here: **the formalism predicts outcomes without telling a story about the in-between.** Whether that is a deficiency of the theory or a property of the world is precisely the measurement problem — and the subject of W2.

12. Next test

Module Q2 Entanglement and Bell's Inequality as the obvious continuation: there it is tested whether the correlations can be explained by local hidden variables — with an inequality that is measurably violated.

Then **W1/W2 (Measuring, Interpreting, Applying / The Interpretations)** as the conclusion of the workshop, for which this module lays the groundwork.

Possible extension v0.2: genuine two-particle calculation for the eraser; decoherence quantitatively; interference with massive particles (C60, module M2); Mach-Zehnder instead of double slit; delayed choice explicitly.

Appendix A — Cross-references

- Practice explanation: `PRAXIS-Dualitas-EN.md` · Companion paper: `BEGLEITPAPIER-Dualitas-EN.md`
- Tool: `DUALITAS.html`
- Code: `dualitas_simulation.py` · Plot: `dualitas_szenen.svg` · Data: `dualitas_results.json`
- **Connecting modules:** M2 optical mechanics (break at λ), M3 oscillation (break at ħ), M1 signal chain (non-uniqueness), 01 double slit (classical), 03 single slit (diffraction)
- **Planned:** Q2 entanglement, W1/W2 philosophy of science

Appendix B — External stocktaking

- **Jönsson (1961)** — electron diffraction at the double slit.
- **Tonomura et al. (1989)** — buildup of the pattern from single electrons.
- **Englert (1996)** — quantitative complementarity relation.
- **Dürr, Nonn & Rempe (1998)** — its experimental test.
- **Scully & Drühl (1982)** — the quantum eraser.
- **Arndt et al. (1999)** — interference of C60 (see module M2).

What the workshop note adds: the test using the log-likelihood ratio with scatter, making the lower bound of discriminability visible; the presentation of complementarity as a continuous balance rather than a switch; the explicit calculation that the sum of the eraser subsets remains structureless — thereby defusing the retroaction narrative; the consistent separation of prediction and interpretation.

Appendix C — Sources

- Jönsson, C. (1961). Elektroneninterferenzen an mehreren künstlich hergestellten Feinspalten. *Zeitschrift für Physik* 161:454–474.
- Tonomura, A. et al. (1989). Demonstration of single-electron buildup of an interference pattern. *American Journal of Physics* 57:117–120.
- Englert, B.-G. (1996). Fringe visibility and which-way information: an inequality. *Physical Review Letters* 77:2154–2157.
- Dürr, S.; Nonn, T.; Rempe, G. (1998). Origin of quantum-mechanical complementarity. *Nature* 395:33–37.
- Scully, M. O.; Drühl, K. (1982). Quantum eraser. *Physical Review A* 25:2208–2213.

Word count: ca. 2030 · Pages: 9 · Version 0.1 · 2026-05-17