Chapter 29: The Delayed-Choice Quantum Eraser Experiment in Fractal T0-Geometry

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The **Delayed-Choice Quantum Eraser (DCQE)** experiment (Kim et al., 2000; Walborn et al., 2002) vividly demonstrates quantum complementarity and entanglement. It appears to imply retrocausality: A delayed decision to erase or retain which-path information seemingly influences the interference behavior of a photon in the past. In the fractal **Fundamental Fractal-Geometric Field Theory (FFGFT)** with **T0-Time-Mass Duality**, this paradox completely resolves. The phenomenon emerges from the global, fractal coherence of the vacuum phase field $\theta(x,t)$, regulated by the single fundamental parameter $\xi = \frac{4}{3} \times 10^{-4}$ (dimensionless). There is no retrocausality merely a nonlocal but causal correlation in the fractal vacuum structure.

In T0, quantum states are excitations of the complex vacuum field $\Phi(x,t) = \rho(x,t)e^{i\theta(x,t)}$. Photons are pure phase vortices ($\delta\rho \approx 0$), whose propagation is guided by gradients of time density $T(x,t)$ (duality $T(x,t)\cdot m(x,t) = 1$). Entanglement is global phase coherence: $\theta_{\text{signal}} + \theta_{\text{idler}} = \theta_{\text{total}} = \text{const}$.

1.1 Symbol Directory and Units

Important Symbols and their Units

Symbol	Meaning	Unit (SI)
ξ	Fractal scale parameter	dimensionless
$\Phi(x,t)$	Complex vacuum field	$\mathrm{kg}^{1/2}/\mathrm{m}^{3/2}$
$\rho(x,t)$	Vacuum amplitude density	$\mathrm{kg}^{1/2}/\mathrm{m}^{3/2}$
$\theta(x,t)$	Vacuum phase field	rad (dimensionless)
$T(x,t)$	Time density	s/m^3
$\psi(x,t)$	Effective wave function	dimensionless
$\Delta\theta$	Phase perturbation	rad
l_0	Fractal correlation length	m
θ_{total}	Global entangled phase	rad
$\langle\theta(x)\theta(x')\rangle$	Phase correlation	rad^2
V	Visibility of interference	dimensionless

Unit check (phase correlation):

$$[\langle\theta\theta\rangle] = \text{dimensionless} + \text{dimensionless} \cdot \ln(\text{m}/\text{m}) = \text{dimensionless}$$

Units are consistent.

1.2 The Problem of Apparent Retrocausality

In the standard model of quantum mechanics, DCQE appears paradoxical: The total distribution at signal detector D0 never shows interference. Only with post-selection (correlation with idler detectors) do subsets with interference (erased) or clumping (which-path) occur even if the idler measurement is delayed.

This leads to misunderstandings about retrocausality. T0 resolves this parameter-free through fractal nonlocality.

1.3 Description of the Experiment

Entangled photon pairs from parametric down-conversion (PDC): - Signal photon double slit detector D0 (movable for scanning). - Idler photon delayed setup with beam splitters and detectors (D1D4).

Without erasure (which-path detectors): No interference in correlated subsets. With erasure (e.g., beam splitter before detectors): Interference in subsets delayed choice only classifies the data.

1.4 Phase Coherence in the T0 Vacuum Structure

The effective wave function is a phase modulation:

$$\psi(x,t) = e^{i\theta(x,t)/\xi}, \tag{1}$$

since photons are pure phase ($\rho \approx \rho_0$).

Fractal correlation:

$$\langle\theta(x)\theta(x')\rangle = \theta_0 + \xi \cdot \ln(|x-x'|/l_0). \tag{2}$$

Unit check:

$$[\xi \cdot \ln(|x-x'|/l_0)] = \text{dimensionless}$$

For entangled pairs:

$$\theta_{\text{signal}}(x) + \theta_{\text{idler}}(x') = \theta_{\text{total}} = \text{constant}. \tag{3}$$

1.5 Derivation of the Erasure Effect

Which-path marking disturbs the idler phase:

$$\Delta\theta_{\text{idler}} \approx \pi \quad \Rightarrow \quad \Delta\theta_{\text{signal}} \approx \pi \quad \text{(through duality)}, \tag{4}$$

randomizes the phase at D0 reduced visibility $V \approx 0$.

Erasure (e.g., 50/50 beam splitter):

$$\Delta\theta_{\text{idler}} \approx 0 \quad \Rightarrow \quad \Delta\theta_{\text{signal}} \approx 0, \tag{5}$$

coherence maintained $V \approx 1$ in correlated subsets.

The "delayed choice" only affects post-selection of events the global phase θ_{total} is always coherent.

Minimal phase uncertainty from fractality:

$$\Delta\theta_{\min} \approx \xi^{3/2}\sqrt{\ln(\xi^{-1})} \approx 4.6 \times 10^{-6}. \tag{6}$$

1.6 Nonlocal Correlation Without Retrocausality

The correlation is fractally conditioned:

$$\Delta\theta_{\text{signal}} \cdot \Delta\theta_{\text{idler}} \geq \xi. \tag{7}$$

This is deterministic and causal no signal transmission backwards.

1.7 Comparison with Other Interpretations

Other Interpretations	**T0-Fractal FFGFT**
Copenhagen: Collapse, observer	Deterministic, vacuum-geometric
Many-Worlds: Branching	Unified fractal phase
Retrocausality models: Time travel	No retrocausality needed
Additional assumptions	Parameter-free from ξ

1.8 Conclusion

The DCQE experiment is no longer a paradox in T0-theory: The apparent retrocausality arises from the global, fractal coherence of the vacuum phase field $\theta(x,t)$. Erasure restores coherence in correlated subsets without changing the past event merely the classification of data. Everything emerges parameter-free from the single scale parameter $\xi = \frac{4}{3} \times 10^{-4}$, and unifies quantum entanglement with Time-Mass Duality as a geometric necessity of the dynamic vacuum.