Title of the experimental proposal

Experimental Investigation of a Modified Delayed-Choice Quantum Eraser Configuration with Signal Path Recombination (D5 Scheme): A Test of Marginal Quantum Statistics under Non-Standard Measurement Conditions

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Collaboration presenting the LoI

Independent research initiative, proposed in collaboration with ELI-NP scientific staff (to be established)

List of authors and institutions with identified spokespersons

Răuț Vlad – Ieromonah Paisie
Chilia „Intrării Maicii Domnului în Biserică"
Sfântul Munte – Schitul Lacu – Grecia
(Cetățenie română)

Proposed spokesperson: Răuț Vlad

Corresponding author: Răuț Vlad (intelinkgov@gmail.com)

Local contact – if any

To be identified within ELI-NP (Optical Laboratory / Quantum Optics expertise)

Scientific case

Background to the research proposal

The delayed-choice quantum eraser (DCQE) experiment (Kim et al.) is a cornerstone demonstration of quantum complementarity, highlighting the interplay between which-path information and interference. In all standard realizations, interference patterns are absent in marginal (single-particle) distributions and can only be recovered through coincidence post-selection.

A modified configuration has been proposed (Wu, 2021), involving recombination of signal photon paths into a single detection channel (D5 geometry). This configuration raises the question of whether the effective projection of the entangled state could alter the observable marginal distribution of the idler photon.

Scientific problem to be tackled

This proposal aims to experimentally probe whether non-standard measurement geometries, specifically signal path recombination, can modify the marginal statistics of entangled photons.

More precisely:

Can a modified DCQE configuration involving signal path recombination induce measurable deviations in the spatial marginal distribution of idler photons, in the absence of coincidence counting?

This question directly addresses:

- the operational limits of the no-signalling theorem
- the role of partial collapse and conditional projection
- the distinction between coherent superposition and statistical mixtures
- the robustness of quantum measurement postulates under modified geometries

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Aims, objectives, assumptions, scope

Aims

- To experimentally test a modified DCQE configuration incorporating signal path recombination (D5 scheme)
- To investigate the structure of marginal detection statistics in entangled photon systems

Objectives

- Implementation of a stable SPDC-based entangled photon source
- Realization of a controlled path recombination geometry for signal photons
- Measurement of the spatial distribution of idler photons without post-selection
- Quantitative comparison with standard quantum mechanical predictions

Assumptions

- Entangled photon pairs are generated via spontaneous parametric down-conversion (SPDC)
- Optical recombination may preserve local phase relationships (to be experimentally verified)

Scope

- Fundamental experimental test in quantum optics
- No prior assumption of superluminal signalling
- Focus on empirical validation of marginal distributions and their invariance

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Methodology

The proposed experiment consists of the following stages:

1. Generation of entangled photon pairs via SPDC in a nonlinear crystal (e.g. BBO), pumped by a coherent laser source
2. Spatial separation of signal and idler photons
3. Implementation of a signal path recombination scheme (D5 configuration), as described in the modified DCQE proposal
4. Precise focusing of the recombined signal photons onto a localized detection region
5. Measurement of the spatial distribution of idler photons using a position-sensitive detection system
6. Statistical analysis of detection patterns:
    - without coincidence filtering (primary objective)
    - with coincidence counting (control measurement)

This experiment represents a controlled test of whether path recombination can modify the operational boundary between conditional and marginal quantum statistics.

Requested Beam(s)

The experiment does not require high-power beams.

Required specifications:

- coherent laser source (continuous wave or pulsed)
- wavelength suitable for SPDC (e.g. 405 nm pump → ~810 nm photon pairs)
- stable beam profile and low phase noise

Targets

- Nonlinear optical crystal (e.g. Beta Barium Borate – BBO)
- Optical recombination system:
    - high-quality mirrors
    - 50:50 beam splitters
    - focusing lenses (including possible high-NA optics)

Instrumentation and detectors

Core components

- Single-photon detectors (APD or SPAD)

- Position-sensitive detector or scanning detection system
- Time-correlated single-photon counting (TCSPC) or coincidence electronics (for calibration)
- Optical table with vibration isolation
- Precision opto-mechanical mounts and alignment systems

Optical components

- Beam splitters (50:50, low-loss)
- High-reflectivity mirrors
- Beam shaping and focusing lenses
- Phase control and fine alignment elements

Optional

- Custom optical recombination module for D5 configuration

Theoretical support

The proposal is grounded in standard quantum optics formalism, including:

- entangled biphoton states generated via SPDC
- second-order correlation functions
- wavefunction projection and conditional measurement

The modified configuration follows the framework proposed in Wu (2021), where signal path recombination leads to an effective projected idler state of the form:

$\Psi_i(x) = \alpha\Psi_i^A(x) + \beta\Psi_i^B(x)$

The experiment explicitly tests whether such a description can manifest at the level of marginal distributions, or whether decoherence and tracing over inaccessible degrees of freedom enforce standard mixture statistics.

Numerical simulations (Python-based) can be provided to model expected distributions under both assumptions.

Envisaged results

Two outcomes are considered:

1. Standard quantum prediction confirmed

- No interference observed in marginal distribution
- Full agreement with the no-signalling theorem
- Experimental validation of robustness of marginal statistics

2. Observable deviation

- Detection of modulation in spatial distribution
- Indicates need for refined theoretical treatment of measurement and projection

Even a null result would provide a valuable experimental confirmation of the stability of quantum no-signalling constraints under non-standard measurement geometries.

Risks and mitigation

Risks

- Decoherence effects reducing visibility
- Imperfect optical alignment
- Detector inefficiencies and noise

Mitigation

- Calibration using standard DCQE configuration
- High-precision alignment procedures
- Statistical averaging over large datasets
- Cross-validation using coincidence measurements

Reference list

- Y.H. Kim et al., *Delayed Choice Quantum Eraser*, Phys. Rev. Lett. 84
- Lee Wen Wu, *Superluminal Communication?* (2021)