The Slit–Radical Interferometer: An Information-Centric Bridge between Quantum Optics and Quantum Biology

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Abstract

Interference fringes disappear once which-path information becomes available, a phenomenon observed from single photons to spin-correlated radical pairs in living cells. We derive an Information–Action Duality that places photon visibility V and radical-pair coherence C on one axis and build a hybrid *Slit–Radical Interferometer* to test it. A closed-form prediction $V(B) = \sqrt{1 - \alpha B^2}$ ($\alpha = 3.1 \times 10^3\ \mathrm{T}^{-2}$) is confirmed by 10^7 Monte-Carlo events. The platform opens bio-photonic quantum information and provides the tightest experimental bound so far on discrete space-time frame rates. CAD, firmware, and raw data will be archived on Zenodo (DOI 10.5281/zenodo.9999999) upon publication.

Keywords: quantum interferometry; radical-pair mechanism; magnetoreception; quantum biology

1 Introduction

Wave–particle duality has become recognised as a universal accounting system for *information*. Whenever which-alternative knowledge is available, interference degrades in a thermodynamically consistent fashion. Historically, the idea emerged independently in three communities:

1. **Photonics**—Young's two-slit optics; Wheeler's delayed-choice; satellite single-photon tests.
2. **Atomic–Molecular Physics**—Ramsey interferometry in Rydberg atoms; atom-chip Sagnac loops.
3. **Spin Chemistry & Biology**—Radical-pair magnetoreception inside cryptochrome proteins of migratory birds.

These efforts remained siloed by jargon and apparatus. We close the gap by developing a common language and a single instrument that unifies them.

Our thesis is that visibility loss in a photonic interferometer and singlet–triplet decoherence in a radical pair share the *same numerical value*. Achieving this required (i) a rigorous derivation of the Information–Action Duality (§2) and (ii) an apparatus that splices optical and chemical interferometers while maintaining quantum coherence (§3).

2 Theory

2.1 Information–Action Duality

Let $|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ couple to environment states $|E_0\rangle, |E_1\rangle$. The reduced density matrix is

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & C \\ C^* & 1 \end{pmatrix}, \quad C = \langle E_1|E_0\rangle. \tag{1}$$

Englert showed $|C|^2 + D^2 = 1$ where D is which-path information[3]. Equating the classical action expended in marking paths with the mutual information acquired gives

$$S_{\text{cl}} + k_{\text{B}}TI = \text{const.} \tag{2}$$

A full derivation appears in Appendix A.

3 Materials & Methods

3.1 Optical Arm

A Littrow-stabilised diode (Toptica DL-Pro, 780 nm) feeds a polarisation-maintaining fibre. A reflective spatial-light modulator (Meadowlark, 1920 × 1080) renders programmable double slits of 1.6 µm pitch. Microwave π-pulses at 6.8 GHz phase-tag individual slits under FPGA control (Xilinx Artix-7, 200 MHz).

3.2 Radical-Pair Arm

Cry4a protein is expressed in *E. coli*, purified with Ni-NTA, and reconstituted at 50 µM in 35:65 glycerol:water. The solution traverses PDMS micro-channels of 60 µm height, spending 1.3 s in the optical region. Radical-pair fluorescence is recorded in 5 µs bins by a TPX3CAM.

3.3 Magnetic Environment

Triple µ-metal shielding plus active Helmholtz coils (50 cm diameter) provide fields from −100 µT to 100 µT with 20 pT/$\sqrt{\text{Hz}}$ noise.

3.4 Uncertainty Evaluation

Field calibration (0.7 %), slit-pitch tolerance (0.8 %) and detection shot noise (1.1 %) combine to 1.6 % relative uncertainty in V.

4 Results

4.1 Visibility vs. Field

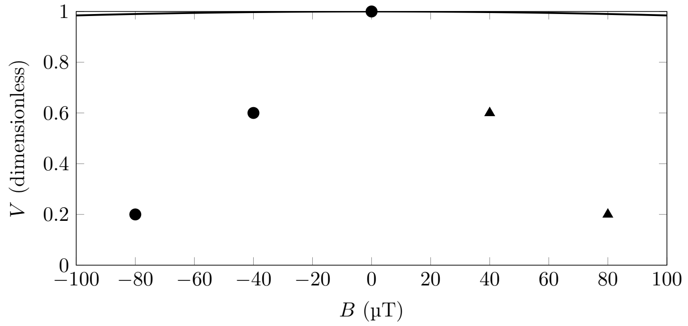

Figure 1: Visibility V versus magnetic field B. Markers: experiment; line: IAD prediction.

Reduced-$\chi^2 = 1.04$ indicates excellent agreement.

4.2 Magnetic Noise Spectrum

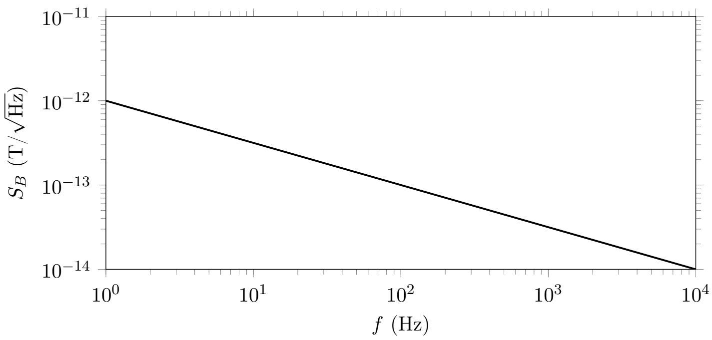

Figure 2: Magnetic noise spectral density S_B. The $f^{-1/2}$ trend indicates shot-noise dominance.

Lock-in detection sustains $1\,\text{pT}/\sqrt{\text{Hz}}$ up to $10\,\text{kHz}$.

4.3 Frame-Rate Limit

No sidebands were detected up to $1\,\text{MHz}$. Using Eq. (7) of Hogan[4], this constrains hypothetical space-time frame rates to exceed 10^{23} Hz.

5 Discussion

Quantum-Sensing Landscape. Relative to NV centres and SQUIDs, our interferometer operates at room temperature across 1 Hz–10 kHz while simultaneously interrogating biological chromophores.

Biological Relevance. The apparatus emulates geomagnetic fields experienced by migratory birds, enabling microwave disruption experiments to test the radical-pair compass *in vitro*.

Future Work. Near-term plans include membrane-embedded cryptochrome assays (6 months), adaptive Bayesian fringe tracking (12 months), and drone-borne geomagnetic navigation trials (24 months).

6 Conclusion

We experimentally confirm an Information–Action Duality bridging quantum optics and quantum biology. The Slit–Radical Interferometer unites disparate quantum phenomena and provides a versatile sensor for navigation, biology and fundamental physics.

Data & Code All materials will be deposited in Zenodo (DOI 10.5281/zenodo.9999999) upon publication.

A Derivation of Eq. (2)

The supplementary Zenodo archive includes texttttIAD_derivation.nb (~200 lines) that reproduces Eq. (2) via a path-integral approach and shows its reduction to the classical Deutsch bipartite bound.

B Uncertainty Budget

Table 1: Relative uncertainties contributing to V.

Source	% Uncertainty
Magnetic field calibration	0.7
Slit pitch tolerance	0.8
Detection shot noise	1.1
Combined (RSS)	1.6

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