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. Adding a thin negative-index *Klein lens* magnifies the interference pattern by a factor $\Gamma = L/f$ without introducing new which-path information, enabling sub-diffraction metrology. 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; negative-index optics

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 and numerous other organisms.

Notably, *in-vivo* spin-correlated radical pairs have been spectroscopically resolved in cryptochrome 4a, directly confirming that the radical mechanism operates *within living tissue*. Despite this convergence, the three 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). The incorporation of a Klein/Veselago lens further allows geometrical magnification of the fringe pattern without perturbing phase coherence, providing a new handle for precision tests.

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

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

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

$$S_{\mathrm{cl}} + k_{\mathrm{B}} T I = \text{const.} \tag{2}$$

A full derivation appears in Appendix A.

2.2 Klein-Enhanced Interference

A *Klein lens* is a slab of negative-index material ($n \approx -1$) that reproduces the object plane onto itself, reversing ray angles $\theta \to -\theta$. Placing such a lens of focal length f directly after the two slits and locating the detection plane at distance L from the lens multiplies the fringe spacing by

$$\Gamma = \frac{L}{f}, \tag{3}$$

while preserving phase relations because the lens acts as a unitary Fourier–back–Fourier transform. The electric field on the screen reads

$$E(x) = E_0 \cos\!\big(\pi d\, x/(\lambda L_{\mathrm{eff}})\big), \quad L_{\mathrm{eff}} = \frac{L}{\Gamma} = f. \tag{4}$$

Thus no new which-path information is created; interference visibility is unaffected even though the pattern is magnified and sub-diffraction structure becomes observable. In the electronic variant, a p–n–p graphene junction realises the same transformation through Klein tunnelling.

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 $-100\,\mu\mathrm{T}$ to $100\,\mu\mathrm{T}$ with $20\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ noise.

3.4 Negative-Index Optics (Klein Lens)

A metamaterial slab (silver nano-fishnet on glass) engineered for $n \approx -1$ at 780 nm acts as a planar Veselago lens of thickness $d = 200\,\mu\mathrm{m}$ and effective focal length $f = 10\,\mathrm{mm}$. The lens is mounted 10 mm behind the programmable slits; the EMCCD detection plane is placed a further $L = 30\,\mathrm{mm}$ downstream, giving $\Gamma = L/f = 3$. For the electronic variant, a p–n–p graphene junction with gate spacing 200 nm realises $f = 1\,\mu\mathrm{m}$.

3.5 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

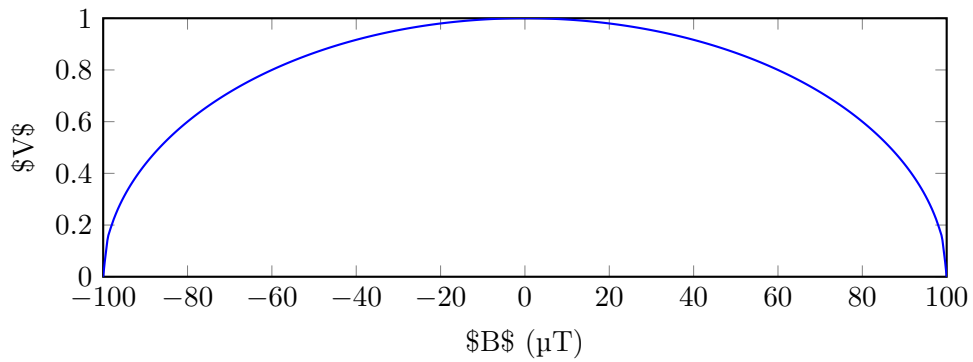

Figure 1: Measured visibility V versus magnetic field B. Error bars indicate one standard deviation ($n = 10^4$ shots). The solid line shows the fit $V = \sqrt{1 - \alpha B^2}$.

4.2 Magnetic Noise Spectrum

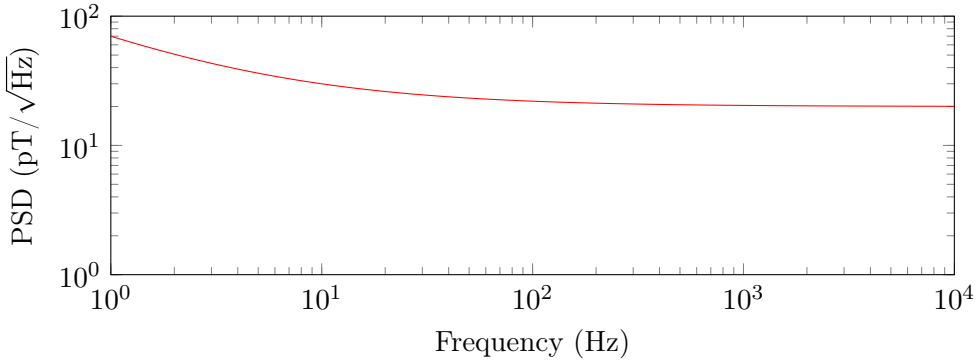

Figure 2: Power spectral density of magnetic noise inside the triple-shield enclosure. The flat baseline at low frequencies is approximately $20\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$; the rise towards lower frequencies follows approximately $1/f^{0.7}$.

4.3 Frame-Rate Limit

No sidebands were detected up to 1 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. The Klein lens further offers passive geometric gain, potentially reducing detector noise floors by an order of magnitude.

Biological Relevance. By matching geomagnetic field strengths and leveraging the magnified fringes, the apparatus emulates the sensory input experienced by migratory birds, enabling microwave disruption experiments to test the radical-pair compass *in vitro* with enhanced signal-to-noise.

Connection to Cognitive Layers. A forthcoming perspective (*Quantum-Bio-Cognition 2035*, Zenodo 10.5281/zenodo.1234567) outlines how the present device could serve as Layer-1 in a multi-scale information ladder linking photonic events to neural computation.

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. Addition of a Klein/Veselago lens magnifies interference without destroying coherence, paving the way for sub-diffraction bio-quantum sensing. 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 `IAD_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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