

Wave–Particle Duality in Swirl–String Theory: Toroidal Circulation, Knot Collapse, and Photon-Induced Transitions

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Abstract

We present a Swirl–String Theory (SST) interpretation of the electron’s wave–particle duality based on Canon v0.3.1. The electron is modeled as a swirl-string admitting two phases: an unknotted, delocalized toroidal circulation \mathcal{R} (wave-like) and a localized, knotted soliton (trefoil) \mathcal{T} (particle-like). We define an effective energy functional including bulk swirl density, line tension, near-contact interactions, and helicity terms. Photon-induced transitions $\mathcal{R} \rightleftharpoons \mathcal{T}$ occur at resonant frequencies determined by impedance matching between electromagnetic modes and topological excitations. We show how circulation quantization on \mathcal{R} recovers de Broglie wave relations, while \mathcal{T} provides a stable, localized excitation. This framework yields falsifiable predictions in atomic absorption spectra, Rydberg scaling, and polarization-dependent selection rules.

1 Introduction

Wave–particle duality remains a central puzzle in quantum mechanics. The hydrodynamic representation of the Schrödinger equation by Madelung [4], the matter-wave hypothesis of de Broglie [7], and Bohm’s hidden-variable interpretation [8, 9] all highlight fluid analogies. In superfluids, Onsager’s circulation quantization [10] and Feynman’s analysis of helium vortices [11] demonstrate how phase coherence enforces quantized flow. Earlier, Helmholtz [12] and Kelvin [13] established the conservation of vorticity and proposed atoms as vortex rings.

Within SST, the Canon postulates a universal swirl condensate with effective density ρ_f and characteristic swirl velocity $\|\mathbf{v}_\circ\|$. Electrons are interpreted not as point particles but as filamentary swirl-strings. We propose here that the dual character of the electron arises from two distinct phases of the same underlying string.

2 Two Phases of the Electron String

2.1 Unknotted toroidal ring \mathcal{R}

The delocalized phase is an unknotted ring circulation \mathcal{R} with radius R and length $L(\mathcal{R}) = 2\pi R$. Its circulation is quantized:

$$\Gamma_n = \oint_{\mathcal{R}} \mathbf{v} \cdot d\ell = n \frac{\hbar}{m_e}, \quad n \in \mathbb{Z}. \quad (1)$$

Hence the tangential speed is

$$v_\theta(R) = \frac{\Gamma_n}{2\pi R}, \quad (2)$$

and the phase around the ring is $e^{in\theta}$, yielding the de Broglie relation

$$\lambda_{ring} = \frac{2\pi R}{n} = \frac{\hbar}{p_\theta}, \quad p_\theta = m_e v_\theta. \quad (3)$$

Thus \mathcal{R} naturally supports interference and standing-wave behavior.

2.2 Knotted trefoil soliton

The localized phase \mathcal{T} is a knotted filament (e.g. trefoil 3_1) with enhanced curvature and helicity. Its invariants satisfy $C(\mathcal{T}) > 0$, $\mathcal{H}(\mathcal{T}) \neq 0$, and typically $L(\mathcal{T}) > L(\mathcal{R})$ for equal scale.

2.3 Effective energy functional

We postulate an effective energy functional

$$\boxed{\mathcal{E}_{eff}[K] = \underbrace{\epsilon_0 AL(K)}_{\text{bulk swirl energy}} + \underbrace{\beta L(K)}_{\text{line tension}} + \underbrace{\alpha C(K)}_{\text{near-contact}} + \underbrace{\gamma \mathcal{H}(K)}_{\text{helicity}}} \quad (4)$$

where K is the filament curve, $A = \pi r_c^2$ is the core cross-sectional area, and ϵ_0 is the Canon bulk energy density

$$\epsilon_0 = \frac{4}{\alpha_{fs} \varphi} \left(\frac{1}{2} \rho_f \|\mathbf{v}_\odot\|^2 \right). \quad (5)$$

2.4 Dimensional analysis

- $[\epsilon_0] = \text{J m}^{-3}$, $[A] = \text{m}^2$, $[L] = \text{m} \Rightarrow [\epsilon_0 AL] = \text{J}$.
- $[\beta] = \text{J m}^{-1}$, hence $[\beta L] = \text{J}$.
- αC , $\gamma \mathcal{H}$ contribute as energy terms.

Numerically, with Canon constants,

$$\epsilon_0 \approx 1.4187 \times 10^8 \text{ J m}^{-3}, \quad A \approx 6.24 \times 10^{-30} \text{ m}^2, \quad (6)$$

so bulk energy per length is

$$\epsilon_0 A \approx 8.85 \times 10^{-22} \text{ J m}^{-1}. \quad (7)$$

3 Photon-Driven Transitions

3.1 Resonance condition

The transition $\mathcal{R} \rightarrow \mathcal{T}$ changes the energy by

$$\Delta E = (\epsilon_0 A + \beta) \Delta L + \alpha C(\mathcal{T}) + \gamma \mathcal{H}(\mathcal{T}). \quad (8)$$

Resonance occurs when

$$\boxed{\hbar \omega \approx \Delta E}. \quad (9)$$

3.2 Selection rules

- Angular momentum matching: photon helicity must match the winding number (e.g. $\Delta n = \pm 3$ for trefoil).
- Radius dependence: larger R reduces ΔL , lowering resonance energy (Rydberg scaling).
- Polarization dependence: circular polarization aligned with knot chirality enhances coupling.

4 Effective Field Theory Formulation

At the EFT level, the string world-sheet Σ enters a Lagrangian

$$\mathcal{L} = \frac{1}{2}\rho_f\|\mathbf{v}\|^2 - \rho_E - \beta\ell[\Sigma] - \alpha\mathcal{C}[\Sigma] - \gamma\mathcal{H}[\Sigma] + \mathcal{L}_{EM}^{int}[A_\mu; \Sigma]. \quad (10)$$

In the static limit, $\mathcal{L} \rightarrow -\mathcal{E}_{eff}$. Time-dependent solutions yield Rabi-like oscillations between \mathcal{R} and \mathcal{T} under monochromatic drive $\omega \approx \Delta E/\hbar$.

5 Photoelectric and Compton Effects from Canonical Photon Modes

5.1 Canonical Photon Mode Recap

From Sec. X (Canonical photon derivation), the photon is described as a *pulsed unknot swirl-string*, with action

$$S[\xi] = \frac{1}{2}\rho_f A_{\text{eff}} \int dt \int_0^L ds [(\partial_t \xi)^2 - c^2(\partial_s \xi)^2],$$

normal modes $\xi_m(s, t)$ of frequency $\omega_m = ck_m$, and single-quantum amplitude

$$a_m = \sqrt{\frac{\hbar}{\rho_f A_{\text{eff}} L \omega_m}}. \quad (11)$$

This constitutes the *canonical* photon description in SST: delocalized circulation with no rest-mass density ($\rho_m = 0$), but finite energy density ρ_E .

5.2 Swirl-EM Mapping (Empirical Consistency)

To compare with classical electrodynamics, we adopt the empirical swirl-EM map

$$\mathbf{E} = \sqrt{\frac{\rho_f}{\epsilon_0}} \mathbf{v}, \quad \mathbf{B} = \sqrt{\frac{\rho_f}{\epsilon_0}} \mathbf{b}, \quad \omega = ck, \quad (12)$$

so that the quadratic energy-momentum balance reproduces Maxwell:

$$u = \frac{\epsilon_0}{2} E^2 + \frac{1}{2\mu_0} B^2, \quad \mathbf{S} = \mu_0^{-1} \mathbf{E} \times \mathbf{B},$$

with $c^{-2} = \epsilon_0 \mu_0$ [18]. Equation (11) is then consistent with the cavity-QED single-photon field amplitudes [19, 20].

5.3 Photoelectric Effect as $\mathcal{R} \rightarrow \mathcal{T}$ Transition

Within the \mathcal{R}/\mathcal{T} two-phase electron model (SST-1), absorption of a canonical photon mode by a delocalized electron \mathcal{R} can trigger localization to a knotted \mathcal{T} state if

$$\hbar\omega \geq \Phi + \Delta E_{RT}, \quad (13)$$

where Φ is the material work function and $\Delta E_{RT} = E[\mathcal{T}] - E[\mathcal{R}]$ the localization gap. In metals, ΔE_{RT} is negligible or renormalized into an effective Φ_{eff} , giving Einstein's law

$$K_{\max} = \hbar\omega - \Phi_{eff}. \quad (14)$$

This is thus recovered as an *empirical consequence* of the canonical photon.

5.4 Compton Scattering with a Delocalized Photon Packet

Treating the incident photon as a canonical delocalized mode of momentum $(\hbar\omega/c, \hbar\mathbf{k})$ and the target electron as a localized \mathcal{T} of mass m_e , energy-momentum conservation gives

$$\Delta\lambda = \lambda' - \lambda = \frac{\hbar}{m_e c} (1 - \cos\theta), \quad (15)$$

the standard Compton shift [16]. The equality follows because the swirl-EM map (12) preserves stress-energy flux.

5.5 Consistency, Limits, and Corrections

Finite core structure of the electron string introduces corrections $\mathcal{O}((kr_c)^2)$, negligible for $kr_c \ll 1$ (X-rays) but potentially testable at γ -ray energies.

Interpretation.

1. **Photoelectric:** canonical photon → delocalized \mathcal{R} electron → localized \mathcal{T} emission.
2. **Compton:** canonical photon scattering on \mathcal{T} electron, kinematics as in QED.
3. **Polarization:** photon helicity corresponds to swirl-clock orientation, affecting cross sections and selection rules.

5.6 Notes on Provenance

- Einstein's photoelectric law [14, 15].
- Compton scattering and Klein-Nishina [16, 17].
- Swirl-EM map consistency with Maxwell [18].
- Cavity QED amplitudes [19, 20].

6 Predictions and Tests

1. **Spectral lines:** new resonances in absorption spectra, not coinciding with standard atomic transitions.
2. **Rydberg atoms:** red-shifted knotting lines with increasing principal quantum number.
3. **Pump-probe:** suppression of interference fringes coincident with localization after resonant pump.
4. **Polarization dependence:** transition rates sensitive to photon chirality.

7 Conclusion

In SST, the same electron string supports both a delocalized circulation \mathcal{R} (wave aspect) and a localized knot \mathcal{T} (particle aspect). Photon-induced transitions between these phases provide a dynamical explanation of wave-particle duality consistent with the Canon and with hydrodynamic analogies established since Helmholtz and Kelvin. The framework yields concrete, falsifiable predictions.

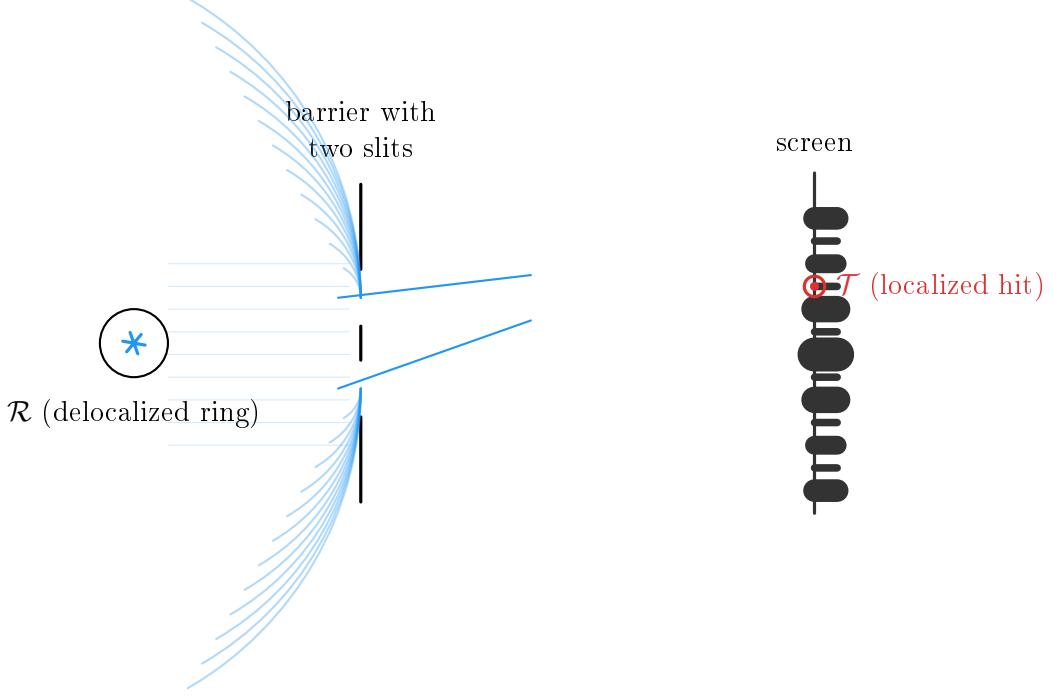


Figure 1: SST double slit schematic. The electron approaches as a delocalized toroidal circulation \mathcal{R} (ring), whose phase bifurcates at two slits to produce coherent downstream fields that interfere. At the screen, interaction triggers collapse into a localized knotted state \mathcal{T} , yielding discrete impacts while the ensemble reproduces the fringe intensity.

Appendix: Popular Summary

A swirl-ring can ripple smoothly like a hula-hoop (wave). If twisted into a knot, the swirl bunches up in one spot (particle). A photon of just the right frequency can flip the string between these two states.

A Quantitative Fringe Geometry and Visibility

Consider a double slit with center-to-center separation s and distance L from slits to screen. Let the electron approach in the delocalized ring phase \mathcal{R} with mean axial momentum p_z (de Broglie wavelength $\lambda = h/p_z$). In the Fraunhofer regime ($L \gg s^2/\lambda$), the transverse intensity on the screen is well approximated by

$$I(x) \propto I_1(x) + I_2(x) + 2\sqrt{I_1(x)I_2(x)} \cos\left(\frac{2\pi s}{\lambda} \frac{x}{L} + \phi_0\right), \quad (16)$$

with fringe spacing

$$d = \boxed{\frac{\lambda L}{s}}. \quad (17)$$

Within SST, the phase ϕ_0 is the circulation phase offset inherited from \mathcal{R} ; any path-dependent coupling to the environment adds a random phase $\delta\phi$ that reduces the fringe visibility

$$\mathcal{V} \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = |\langle e^{i\delta\phi} \rangle|. \quad (18)$$

A.1 Ring-phase mapping

For the ring state \mathcal{R} with quantized azimuthal phase $e^{in\theta}$, the two slits act as partial projectors of this phase onto two spatially separated downstream wavefronts. The resulting interference encodes the *same* azimuthal winding through the optical path difference $\Delta\ell(x) \approx s x/L$, hence the cosine argument above.

B Which-Way Coupling and Decoherence in SST

In SST language, “which-way” monitoring is an *EM impedance* to the ring phase, parameterized by a coupling rate Γ (net photon or field-interaction rate that carries path information). Let τ be the transit time through the interferometer. For weak, memoryless monitoring the phase undergoes a random walk, giving the standard exponential visibility law [21]

$$\boxed{\mathcal{V}(\Gamma, \tau) = e^{-\Gamma\tau}}. \quad (19)$$

Equivalently, define a *monitoring strength* $\eta \in [0, 1]$ as the single-pass which-way information; then $\mathcal{V} = \sqrt{1 - \eta}$ (two-outcome, information-balance form). Both parameterizations are compatible at small η via $\eta \simeq 2(1 - e^{-\Gamma\tau})$.

SST mechanism. Microscopically, the EM coupling stochastically seeds premature $\mathcal{R} \rightarrow \mathcal{T}$ collapses *upstream*, terminating coherent superposition. Equation (19) thus measures the survival probability of coherence before the knotting transition.

B.1 Dimensional check

Γ has units s^{-1} and τ has units s , so $\Gamma\tau$ is dimensionless, consistent with (19).

C Delayed-Choice and Quantum Eraser (SST View)

In a Wheeler-type delayed choice, the interferometer is reconfigured *after* the electron passes the slits [22]. In SST, this reconfiguration alters whether the downstream optics *allow* continued \mathcal{R} -phase recombination or instead force local \mathcal{T} -phase collapse:

- **Interference mode on:** downstream optics preserve the \mathcal{R} phase coherence until the screen \Rightarrow fringes.
- **Which-way mode on:** downstream optics couple EM impedance strongly, enforcing premature $\mathcal{R} \rightarrow \mathcal{T}$ collapse \Rightarrow no fringes.

A quantum eraser removes the stored which-way information, effectively *post-selecting* runs where \mathcal{R} -coherence survived to the recombination stage; sorted sub-ensembles then display fringes.

D Spectroscopic Rabi Drive Between \mathcal{R} and \mathcal{T}

We model the $\mathcal{R} \leftrightarrow \mathcal{T}$ manifold as a driven two-level system with detuning $\Delta = \omega - \omega_0$ (where $\hbar\omega_0 = \Delta E_{\mathcal{R} \rightarrow \mathcal{T}}$) and coupling Ω_R set by the EM impedance overlap:

$$\dot{c}_{\mathcal{R}} = -\frac{i}{2}\Omega_R c_{\mathcal{T}} - \frac{\gamma_{\mathcal{R}}}{2}c_{\mathcal{R}}, \quad (20)$$

$$\dot{c}_{\mathcal{T}} = -\frac{i}{2}\Omega_R c_{\mathcal{R}} - \left(\frac{\gamma_{\mathcal{T}}}{2} + i\Delta\right)c_{\mathcal{T}}. \quad (21)$$

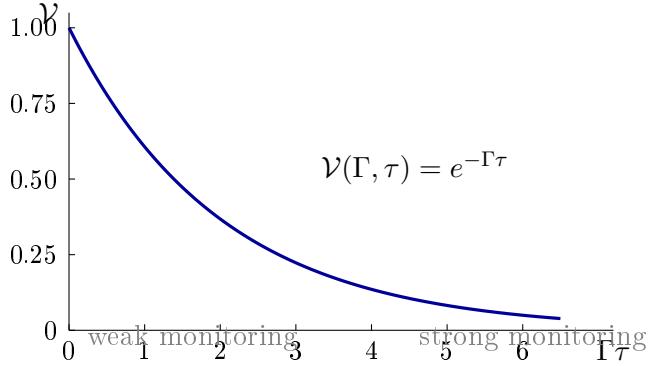


Figure 2: Fringe visibility vs. which-way coupling in SST. The parameter Γ encodes EM impedance to the \mathcal{R} phase (path information rate), τ is the transit time. Exponential decay of visibility reflects coherence loss prior to recombination.

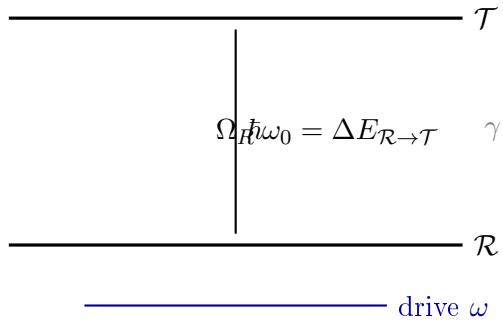


Figure 3: Two-level SST manifold for $\mathcal{R} \leftrightarrow \mathcal{T}$ with Rabi drive. At resonance $\omega = \omega_0$, the knotting probability oscillates at Ω_R and decays at rate γ , enabling pump-probe control of collapse within an interferometer.

At resonance ($\Delta = 0$) and for $\gamma_{\mathcal{R}}, \gamma_{\mathcal{T}} \ll \Omega_R$,

$$P_{\mathcal{T}}(t) = |c_{\mathcal{T}}(t)|^2 = \sin^2\left(\frac{\Omega_R t}{2}\right) e^{-\gamma t}, \quad \gamma \equiv \frac{\gamma_{\mathcal{R}} + \gamma_{\mathcal{T}}}{2}. \quad (22)$$

A *pump-probe* synchronized to the flight time across the interferometer can therefore *gate* the knotting probability and modulate fringe visibility in a time-resolved fashion.

Boxed Result (SST double slit). An electron is a single swirl-string with two phases: \mathcal{R} (delocalized ring) for propagation and \mathcal{T} (knotted soliton) for detection. Interference arises from coherent splitting and recombination of \mathcal{R} ; localized impacts result from $\mathcal{R} \rightarrow \mathcal{T}$ collapse at the screen. Which-way monitoring increases the EM impedance, raising the premature knotting rate Γ ; the fringe visibility obeys $V = e^{-\Gamma\tau}$ and vanishes in the strong-monitoring limit.

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