[1] [2]

A Relational Resolution of the Duality of Matter and Radiation

Hamid Naghieh[1]

[1] *Independent Researcher*

The duality of matter and radiation is traditionally framed as an intrinsic paradox of quantum systems. In part I, we propose it can be reinterpreted as a relational observer dependent-relative phenomenon. This relational resolution of wave–particle duality aligns with foundational experiments of quantum theory. The wave/particle behavior emerges from observer's relative velocity/position with respect to the quantum entity under observation. The wave nature is precived by a rest-observer co-moving with the entity under observation. The particle nature is the relative view of a non co-moving observer with non-zero relative velocity.

Part-II Provides compelling evidence supporting the part-I claim. We revisit two foundational experiments–the Davisson–Germer electron scattering experiment (1927) and the Merli–Missiroli–Pozzi (MMP) biprism interference experiment (1976). By re-examining the conditions under which interference patterns emerge, it is argued that wave-particle duality behavior is not intrinsic to individual particles but arises from coherent ensembles of monoenergetic, indistinguishable quantum entities. This interpretation challenges conventional quantum narratives and offers a physically grounded and testable alternative to wave–particle duality.

Part III Discusses Measurement, Superposition, and Apparatus Coupling. We argue that the uneasy nature of the epistemological conclusions of quantum mechanics may be rectified under relational resolution. We conclude that any quantum relational interaction can be interpreted as a superposition of "initial" states in "space" and superposition of "final" states in "time", and together they form a superposition in "spacetime".

Keywords: wave-particle duality; Double slit experiment; Matter-Radiation duality; Measurement problem; relational two slit experiments.

Part I

Wave–particle duality has long stood as a central mystery in quantum mechanics, famously illustrated by the double-slit experiment and the scattering of electrons by crystalline surfaces [69]. Niels Bohr's principle of complementarity asserts that wave and particle aspects are mutually exclusive yet jointly necessary for a complete description of quantum phenomena [67]. However, this duality has often been treated as an intrinsic property of quantum systems, independent of the observer's state.

In this work, we challenge that assumption by proposing that duality arises from the observer's relative motion with respect to the entity under observation, at different stages of the experiment. This perspective aligns with relational quantum mechanics [61], where physical states are not absolute but depend on the observer's frame of reference. We develop this idea through re-examining a series of well known experiment. We will propose verifiable experiments, culminating in a unified relational framework that connects observer-relative velocity, coherence, and decoherence.

Let us consider the canonical double-slit experiment with electrons. In the initial stage, the electron beam enters the apparatus and passes through the slits. At this stage the observer[3] is implicitly assumed to be co-moving with the beam—(zero relative velocity with the entity)i.e., $v_{\text{observer}} = v_{\text{group}}$—This observer perceives a wave behavior. The system behaves as a coherent wavefunction superposition: $\Psi(x,t) = \Psi_1(x,t) + \Psi_2(x,t)$, where Ψ_1 and Ψ_2 correspond to the wavefunctions through each slit. In the final stage, the beam reaches the detection screen. Here, the observer is implicitly assumed to be non-co-moving with the entity (zero relative velocity with the screen) ($v_{\text{observer}} \neq v_{\text{group}}$). This observer perceives localized particle-like impacts, consistent with the probability density $|\Psi(x,t)|^2$. This shift in observational perspective offers a new interpretation of duality: wave behavior dominates in co-moving frames, while particle behavior emerges in non-co-moving frames. The transition is not a collapse in the traditional sense, but a change in relational description.

The wavefunction of a beam with transverse velocity variation can be expressed as:

$$\Psi(x,y,t) = \Psi_0(x,y,t)\, e^{i\phi(x,y)}, \tag{1}$$

where $\phi(x,y)$ is a position-dependent phase induced by transverse momentum.

For a beam with transverse velocity field $v_\perp(x,y)$, the local transverse momentum is $p_\perp(x,y) = m\, v_\perp(x,y)$.

[1] hamidnaghieh3@gmail.com

[2] https://orcid.org/0000-0002-0205-0947

[3] Here the observer is Secial Theory of Relativity's relative reference frame endowed with a set of coordinate basis.

Over a propagation distance L, the accumulated phase becomes:

$$\phi(x,y) \approx \frac{1}{\hbar}\int_0^L \frac{p_\perp(x,y)}{v_{\text{group}}}dx \approx \frac{p_\perp(x,y)\,L}{\hbar\, v_{\text{group}}}. \quad (2)$$

Alternatively, using a small-angle approximation with transverse wavevector $k_\perp(x,y) = k\,\theta(x,y)$ and $k = 2\pi/\lambda$, the phase becomes:

$$\phi(x,y) \approx k_\perp(x,y)\,x = k\,\theta(x,y)\,x. \quad (3)$$

This formulation highlights that phase dispersion arises from angular spread θ or transverse momentum spread $\Delta p_\perp$. Interference is suppressed when the phase variation across the beam width w exceeds one fringe period:

$$\Delta\phi \gtrsim 2\pi. \quad (4)$$

Angular form: If the beam has an angular divergence $\Delta\theta$, then across a width w the phase difference is

$$\Delta\phi \approx k\,\Delta\theta\,w, \quad (5)$$

where $k = 2\pi/\lambda$ is the wave number. The decoherence condition becomes

$$k\,\Delta\theta\,w \gtrsim 2\pi \quad \Rightarrow \quad \Delta\theta \gtrsim \frac{\lambda}{w}. \quad (6)$$

Momentum form: Since transverse momentum is related to angular spread by $\Delta p_\perp \approx p\,\Delta\theta$ with $p = h/\lambda$, we can write

$$\Delta\phi \approx \frac{\Delta p_\perp\, w}{\hbar}. \quad (7)$$

Thus the threshold condition is

$$\Delta p_\perp \gtrsim \frac{2\pi\hbar}{w}. \quad (8)$$

Dividing by the particle mass m gives a velocity spread criterion:

$$\Delta v_\perp \gtrsim \frac{2\pi\hbar}{mw}. \quad (9)$$

This provides a dimensionally consistent threshold for transverse velocity spread. The earlier condition $v_\perp > \lambda/w$ is more accurately interpreted as an angular threshold $\Delta\theta \gtrsim \lambda/w$.

Coherence length interpretation: Define the transverse coherence length as

$$\ell_c \sim \frac{\lambda}{\Delta\theta}. \quad (10)$$

The condition for interference is then simply

$$\ell_c \gtrsim w. \quad (11)$$

That is, the coherence length must be at least as large as the beam width for fringes to be visible [77, 79].

1. OBSERVER-DEPENDENT OUTCOMES WITH TWO VELOCITY SCALES

Co-moving observer: ($v_{\text{observer}} \approx v_{\text{group}}$): Wave behavior dominates; coherence is preserved along the beam. Interference visibility is governed by $\Delta v_\perp$. Large $\Delta v_\perp$ destroys fringes even in co-moving frames due to phase dispersion across w.

Non-co-moving observer: ($v_{\text{observer}} \neq v_{\text{group}}$): Particle behavior dominates; relative motion enhances decoherence. Additional transverse dephasing has marginal effect on already localized outcomes.

Collimation and Apertures: Goal: Minimize $\Delta\theta$ and $\Delta p_\perp$. Metric: Measure fringe visibility $V(w)$ to estimate ℓ_c.

Phase Diagnostics: Use phase-contrast or off-axis electron holography to map $\phi(x,y)$. Extract $\Delta\theta$ and $\Delta p_\perp$ spatially.

Magnetic Field Gradients: Deflection radius: $R = p/(qB)$, angle $\theta \approx L/R = qBL/p$. Transverse momentum spread: $\Delta p_\perp \approx qBL$. Decoherence threshold: $qBL \gtrsim 2\pi\hbar/w$.

Electric Fields and Optical Potentials: For neutral beams, use light-shift gradients or magnetic potentials to control $\Delta\theta$.

Moving Detector Stage: Sweep v_{observer} and record $V(v_{\text{observer}})$ at fixed $\Delta\theta$. Expected trend:

$$V(v_{\text{observer}}) \approx V_0 \exp\left[-\alpha|v_{\text{observer}} - v_{\text{group}}|\right], \quad (12)$$

with α determined by detector coupling and interaction time.

Beam Width Dependence:

$$V(w) \to 0 \quad \text{when} \quad \Delta p_\perp\, w/\hbar \gtrsim 2\pi. \quad (13)$$

Wavelength Dependence: Longer λ increases ℓ_c, raising tolerance to $\Delta\theta$. Atom and neutron beams are more robust than fast electrons.

Wave–Particle Duality: Duality is governed by $v_{\text{observer}} - v_{\text{group}}$ (macroscopic) and $\Delta v_\perp$ (microscopic).

Decoherence in Open Systems: Transverse kinematic disorder acts as an internal environment. Off-diagonal density matrix terms decay when either velocity mismatch or phase spread exceeds threshold.

Relational Quantum Theory: Relative motion determines which aspects of the state are operationally accessible. Coherence is observer- and apparatus-dependent.

1.1. Specific Experimental Test for $\Delta v_\perp$

Objective: Quantify visibility collapse as a function of controlled $\Delta v_\perp$.

Setup:

- Coherent, collimated electron beam.
- Adjustable slit width w.

- Uniform magnetic field B over length L to induce $\Delta p_\perp \approx qBL$.
- High-resolution screen to compute V via Fourier contrast.

Procedure:

- Baseline: $B \to 0$, measure $V_0(w)$.
- Scan: Increase B, record $V(B)$ for each w, λ.
- Fit: Identify B_c where V collapses; compare to:

$$qB_cL \approx \frac{2\pi\hbar}{w}. \tag{14}$$

Predictions:

- Low $\Delta v_\perp$: $V \approx V_0$.
- Above threshold: Rapid decay in V, consistent with $\Delta p_\perp w/\hbar \gtrsim 2\pi$.

1.2. Integration into Relativistic Regime

For high-energy beams, replace $p \to \gamma mv$ and retain $\Delta p_\perp \approx qBL$. The phase condition becomes:

$$\Delta\phi \approx \frac{\Delta p_\perp\, w}{\hbar} = \frac{qBL\, w}{\hbar} \gtrsim 2\pi. \tag{15}$$

(a) Spin Systems Analogy: Spin projections are relational to the measurement axis.

Hypothesis: Observer motion relative to the beam may influence whether spin is perceived as coherent superposition or collapsed eigenstate.

Experiment: Moving Stern–Gerlach detectors.

Prediction: Co-moving $\to$ coherent spin statistics. Non-co-moving $\to$ enhanced projection collapse.

(b) Entanglement Setup: SPDC photon pairs, one detector stationary, one moving.

Prediction: Stationary $\to$ standard Bell violation. Moving $\to$ possible phase/time-dilation induced deviations in correlation coefficients.

Implication: Tests whether entanglement correlations are invariant under relative motion, or subtly frame-dependent.

To formalize this idea, we embed it within the Dirac equation:

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0, \tag{16}$$

where γ^μ are the Dirac gamma matrices and m is the particle mass [62]. Under a Lorentz transformation Λ, the spinor transforms as:

$$\Psi'(x') = S(\Lambda)\Psi(x), \tag{17}$$

with $S(\Lambda)$ representing the spinor representation of the Lorentz group.

The probability current $J^\mu = \bar{\Psi}\gamma^\mu\Psi$ behaves differently depending on the observer's frame. In co-moving frames, J^μ aligns with wave propagation, while in non-co-moving frames, boosts distort J^μ, producing localized divergences consistent with particle detection.

Relative velocity introduces momentum shifts:

$$\Delta p \sim m(v_{\text{observer}} - v_{\text{group}}), \tag{18}$$

which modify the density matrix:

$$\rho' = \int \Psi(p + \Delta p)\Psi^*(p)\, dp. \tag{19}$$

This leads to accelerated decoherence as Δp increases, suppressing off-diagonal terms and reducing interference visibility.

Additionally, transverse velocity variations $\Delta v_\perp$ across the beam's cross-section introduce position-dependent phase shifts:

$$\Psi(x, y, t) = \Psi_0(x, y, t)e^{i\phi(x,y)}, \quad \phi(x, y) \approx \frac{\Delta p_\perp x}{\hbar}. \tag{20}$$

Interference is suppressed when:

$$\Delta\phi \approx \frac{\Delta p_\perp w}{\hbar} \gtrsim 2\pi, \tag{21}$$

where w is the beam width. This yields a Gaussian decay law for visibility:

$$V = V_0 \exp\left[-\left(\frac{\Delta v_\perp w}{\lambda}\right)^2\right], \tag{22}$$

consistent with coherence theory [79].

Combining both effects, we propose a unified visibility law:

$$V(v_{\text{observer}}, \Delta v_\perp) = V_0 \exp\left[-\alpha|v_{\text{observer}} - v_{\text{group}}|\right] \exp\left[-\left(\frac{\Delta v_\perp w}{\lambda}\right)^2\right]. \tag{23}$$

We propose three key experiments to test this framework.

First instead of a single electron beam source we could have a perpendicular arrey of sources with variable electron velocity. The beams from all sources could then be adjusted to produce a single total beam with $\Delta v_\perp$.

Second if we could place the detector on a motorized stage and synchronize its velocity with the beam. As v_{observer} deviates from v_{group}, record the transition from interference to localization. This tests the external decoherence channel.

Finally we could apply a magnetic field perpendicular to the beam to induce $\Delta v_\perp$. Measure visibility as a function of B, w, and λ. This tests the internal decoherence channel and validates the threshold condition.

This framework extends naturally to spin systems. In a Stern–Gerlach experiment, co-moving detectors may register coherent spin superpositions, while non-co-moving detectors collapse the spin state into eigenstates. This suggests that spin projection outcomes are also observer-relative.

Entanglement experiments, such as those involving SPDC photon pairs [78], may reveal frame-dependent deviations in correlation coefficients. While standard quantum mechanics predicts Lorentz-invariant violations of Bell's inequalities [76], our hypothesis suggests that relative motion could introduce subtle phase shifts or time dilation effects upon testing.

2. BROADER RELATIONAL IMPLICATIONS

This framework integrates relativity and quantum mechanics by treating observer-relative velocity as a unifying relational parameter. Decoherence and wavefunction collapse emerge as relational phenomena, not absolute events. The model aligns with the theory of open quantum systems [79], where environmental and relational factors define observable outcomes.

At cosmological scales, observers with vastly different velocities may interpret quantum fields differently, suggesting new avenues for quantum cosmology and the interpretation of cosmic coherence.

Constraint: Our $|v_{observer} - v_{group}|$-dependent visibility should be interpretable as changing D via detector coupling or timing/bandwidth effects, to avoid conflict with these established relations. A direct claim that velocity alone collapses waves independent of information channels would be challenged by these results. The "relative velocity" is often taken to be a relative velocity in the same rest frame, same coordinate basis. However, observations from different reference frames with relative velocity (different basis) must be compared cross frame to observe relativistic effects. Put differently the relative position of the detector/observer is of paramount importance.

2.1. Position, worldline, and detector response as the real drivers

- Position and worldline: The detector's spacetime trajectory determines which parts of the wavefield it samples (its effective window in space and time). Changing $v_{observer}$ shifts the detector's sampling kernel in spacetime, not just its speed. This alters overlap with the beam's coherent modes, which directly maps to distinguishability D and visibility V.

- Response functions: Motion changes detector integration time, spectral bandwidth, and spatial resolution in the detector's proper frame. Cross-frame, these translate to different filter functions on the field. Visibility reduction arises because the detector's filter increases which-path information (D), not because "velocity collapses waves" by itself.

2.2. Reconciling with complementarity and QFT covariance

- Complementarity (Englert–Greenberger–Yasin): Our $V(|v_{observer} - v_{group}|)$ is interpretable as $V(D(v_{observer}))$, where detector motion modifies D via changed coupling, timing, and sampling. Thus $V^2 + D^2 \leq 1$ remains intact. It's not velocity per se; it's velocity-induced changes in the information channel.

- Covariance: Probabilities and currents transform covariantly. Collapse-like behavior must enter through open-systems dynamics (detector-system coupling and environmental interactions), not through boosts alone. Our cross-frame comparison respects this by transforming the state (spinor/wave) and the detector response, then computing operationally accessible observables.

- What is meant by "velocity causes collapse" is: "The Detector motion and position modulate the accessible coherence through their spacetime sampling kernel and response function, which increases distinguishability D and reduces visibility V."

- Explicit cross-frame pipeline:

  1. Transform the beam state: $\Psi \to S(\Lambda)\Psi$, $J^\mu \to \Lambda^\mu{}_\nu J^\nu$.
  2. Transform detector response: $R(x) \to R'(x')$, including timing window, bandwidth, and spatial PSF in the detector's proper frame.
  3. Compute measurable rates: $P = \int R'(x')|\Psi'(x')|^2 d^4x'$, and extract V, D.
  4. Attribute V reduction to increased D induced by motion-altered R', not to boosts alone.

- Emphasize detector position: The relative position and trajectory (not just speed) set phase alignment and mode overlap. A moving detector crossing fringes at speed $v_{observer}$ samples an effectively time-averaged intensity, which increases path distinguishability (via temporal tagging) and lowers visibility.

- Visibility law reinterpreted:

  $V(v_{observer}, \Delta v_\perp)$
  $= V_0 \exp[-\alpha|v_{observer} - v_{group}|] \exp\left[-\left(\frac{\Delta v_\perp w}{\lambda}\right)^2\right]$

  Now define α from a detector response model:

$$\alpha = \kappa \cdot \tau_{\text{eff}}(v_{observer}) \cdot BWD(v_{observer})$$

where τ_{eff} is effective integration time in the detector's proper frame and BWD is a bandwidth/dispersion factor that quantifies which-path leakage. This makes V a function of D through response parameters.

- Distinguishability mapping:

$$D \approx D_0 + \chi \cdot |v_{observer} - v_{group}| + \xi \cdot \Delta\omega_{\text{eff}}(v_{observer})$$

with $\Delta\omega_{\text{eff}}$ the motion-induced spectral mismatch between arms/modes. Then $V \approx \sqrt{1 - D^2}$ in regimes where the information-theoretic bound is tight, ensuring formal consistency.

- It's not "velocity collapses waves"; it's "motion and position of the detector reshape the information channel and spacetime sampling of the field, increasing distinguishability and reducing visibility."
- Always compare observations cross-frame by transforming both the state and the detector response.
- Keep the detector's relative position and worldline explicit; they determine the phase alignment and coherence actually measured.

3. RELATIVISTIC QFT CONSISTENCY

The core principle is that probabilities and currents transform covariantly; frame changes do not create collapse. Any observer-motion effect must be mediated by detector–system coupling, not kinematics alone. The use of the spinor Lorentz transform $S(\Lambda)$ is compatible; collapse-like behavior must enter via open-systems decoherence, not pure boosts [84].

3.1. Unified Visibility Model Mapped to Complementarity

Motion-induced decoherence can be mapped to distinguishability:

$$D \equiv D\big(|v_{observer} - v_{group}|, \tau, \eta\big), \quad V = \sqrt{1 - D^2} \approx 1 - \tfrac{1}{2}D^2. \tag{24}$$

For small D, fit

$$D \approx \beta |v_{observer} - v_{group}| \tag{25}$$

so that

$$V \approx V_0 \exp[-\alpha |v_{observer} - v_{group}|], \tag{26}$$

with $\alpha \approx \beta$ as an effective parameter extracted from detector bandwidth experiments.

3.2. Transverse Coherence Thresholds with Fields

Use $\Delta p_\perp \approx qBL$ to set the collapse field:

$$qB_c L \gtrsim \frac{2\pi\hbar}{w}. \tag{27}$$

Example: 100 keV electrons ($p \approx \sqrt{2mE}$), $w = 10\,\mu$m, $L = 0.1$ m $\Rightarrow B_c \gtrsim \frac{2\pi\hbar}{qwL} \sim 1.0 \times 10^{-4}$ T. This is experimentally accessible and provides a clean test of the $\Delta v_\perp$-driven visibility law.

3.3. Fraunhofer Fringe Spacing and Coherence Length Extraction

Measure

$$s = \frac{\lambda L}{d} \tag{28}$$

and fit visibility to

$$V(w) \sim \exp\left[-\left(\frac{w}{\ell_c}\right)^2\right]. \tag{29}$$

Extract ℓ_c as a function of beam energy and apertures, comparing electrons vs. atoms vs. molecules to validate universality claims across particle types.

3.4. Motion-Induced Phase and Timing Skew

In moving-detector tests, include Doppler-like sampling effects:

$$\tau' = \tau\left(1 - \frac{v_{observer}}{c}\right) \quad \text{for photons,} \tag{30}$$

or spatial sampling shift

$$\Delta x = v_{observer}\,\tau \quad \text{for massive beams.} \tag{31}$$

Model $D(\tau')$ to connect motion to distinguishability and visibility within established duality bounds.

4. ELECTRON DOUBLE SLIT WITH MOVING DETECTOR

We use a moving phosphor/CCD stage to measure V vs. $v_{observer}$ at fixed $\Delta\theta$. Fit α and compare with information-theoretic D extracted from detector response functions; ensure consistency with $V^2 + D^2 \leq 1$.

4.1. Electron Biprism Interferometer with Uniform Magnetic Field

Scan B and w; verify collapse at

$$\frac{qBLw}{\hbar} \approx 2\pi. \tag{32}$$

Compare with historical electron optics constraints (Davisson–Germer collimation) and modern TEM interferometry practice.

4.2. Atom/Neutron Interferometers on Moving Platforms

Measure visibility vs. platform velocity. Separate Sagnac/acceleration phases from visibility changes by controlling geometry. This directly tests the external channel without confounding internal $\Delta v_\perp$.

4.3. Photonic Mach–Zehnder Delayed Choice with Moving Detector

Quantify visibility change due to motion-induced timing window shifts. Benchmark against quantum eraser duality–entanglement relations to ensure compatibility.

5. SUPPORTING EXPERIMENTS WITH QUANTITATIVE ANALYSIS

5.1. Davisson–Germer Electron Diffraction

The core observation is that the Electron scattering off Ni(111) produces angular-resolved intensity peaks matching Bragg condition when using de Broglie wavelength $\lambda = h/p$. For electron kinetic energy E, $\lambda \approx h/\sqrt{2m_e E}$. At $E \sim 54$ eV, $\lambda \approx 1.67$ Å, consistent with Ni lattice spacing, yielding constructive interference at specific angles by Bragg's law $2d \sin\theta = n\lambda$. This establishes the baseline requirement: coherent, monoenergetic beams produce wave-like outcomes if apparatus geometry supports phase-ordered scattering.

Relevance: Our transverse-spread threshold $\Delta p_\perp w/\hbar \gtrsim 2\pi$ maps to the need for angular collimation so that multiple crystal planes contribute phase-coherently; otherwise diffraction peaks wash out. In terms of angular divergence, requiring $\Delta\theta \lesssim \lambda/w$ is consistent with the classic beam-collimation demands in electron diffraction.

Numerical illustration: For $w = 0.5$ mm and $\lambda = 1.67 \times 10^{-10}$ m, $\Delta\theta \lesssim \lambda/w \sim 3.3 \times 10^{-7}$ rad — explains why electron diffraction historically uses crystalline targets rather than millimeter slits; achieving such small divergence is nontrivial without crystalline ordering.

5.2. Single-Electron Double-Slit (Tonomura)

Core observation: Individual electron impacts build up a sinusoidal fringe pattern with spacing $s \approx \lambda L/d$ in Fraunhofer regime, where L is screen distance and d slit separation. Visibility V depends critically on transverse coherence: beam collimation and monochromaticity control $\Delta v_\perp$ and $\Delta p_\perp$ across the slit width.

Quantitative link: Our Gaussian visibility law

$$V \approx V_0 \exp\left[-\left(\frac{\Delta v_\perp w}{\lambda}\right)^2\right]$$

can be recast via $\Delta v_\perp = \Delta p_\perp/m$ and $\Delta p_\perp \sim \hbar/\ell_c$ to show $V \sim \exp\left[-(w/\ell_c)^2\right]$. This aligns with the empirical need in Tonomura's setup for high transverse coherence to sustain contrast over the illuminated aperture.

Numerical illustration: For 50 keV electrons, $\lambda \approx 5.5 \times 10^{-12}$ m, $d = 1\,\mu$m, $L = 1$ m $\Rightarrow s \sim 5.5$ mm. To maintain $V > 0.5$, require $w/\ell_c \lesssim \ln 2$, implying $\ell_c \gtrsim w$. This is consistent with the careful aperturing and biprism techniques used to ensure path indistinguishability.

5.3. Quantum Eraser

Core observation: Introducing which-path markers reduces visibility per duality relations; conditional post-selection "erases" path information and restores fringes. Modern analyses cast this in duality–entanglement trade-offs, making visibility a resource contingent on information flow rather than intrinsic particle properties.

Relevance: Our "external decoherence" via $v_{observer}$ can be positioned as altering effective information-access channels or coupling—if motion changes detector integration time or frequency response, it modulates distinguishability and hence V. While standard formulations are information-theoretic, our kinematic parameter $|v_{observer} - v_{group}|$ can be mapped onto detector bandwidth-induced which-path leakage, consistent with duality frameworks.

Quantitative link: Englert-type relations $V^2 + D^2 \leq 1$ can be parameterized with D as a function of detector coupling $g(v_{observer})$, e.g., $D \propto g(v_{observer})$. Then $V \approx 1 - D^2$ complements our exponential decay ansatz at small D, showing a plausible first-order equivalence near $D \ll 1$.

5.4. Wheeler Delayed Choice

Core observation: Whether interference or which-path detection occurs can be decided after the photon traverses the first beam splitter. Experiments show outcomes match the late choice, emphasizing configuration/observer context over intrinsic "particle history".

Relevance: Supports the notion that observer-relative configuration (and by extension relative motion, if it changes the effective configuration or measurement coupling) determines the observed regime. Our moving-detector experiment is a kinetic analog of changing the second beam splitter presence, controlling visibility via $|v_{observer} - v_{group}|$.

5.5. Large-Molecule Interference

Core observation: C_{60} and more complex molecules exhibit far-field diffraction/interference with visibility limited by internal and external decoherence. Phase-coherence constraints scale with molecular mass and environmental coupling; transverse coherence must be strong to avoid fringe washing due to $\Delta\theta$ and momentum diffusion.

Quantitative link: The condition $\Delta p_\perp w/\hbar \gtrsim 2\pi$ is stringent for heavy molecules; thermal emission, scattering, and rotational states increase $\Delta p_\perp$. Our thresholds predict visibility collapse beyond critical B, L, or aperture sizes; this matches decoherence-limited contrast in molecule interferometry.

Numerical illustration: For C_{60} at $v \sim 200$ m/s, $\lambda \sim h/(mv) \approx 2.5 \times 10^{-12}$ m; with $w = 10\,\mu$m, angular tolerance $\Delta\theta \lesssim \lambda/w \sim 2.5 \times 10^{-7}$ rad — explains why elaborate collimation and ultra-high vacuum are essential.

5.6. Atom and Neutron Interferometry

Core observation: Neutron interferometers and atom interferometers measure phases from gravitational, inertial, and electromagnetic potentials, with high-contrast fringes when coherence and apparatus motion are controlled. Phase shifts can be calculated via action integrals; visibility depends on beam coherence and mechanical stability.

Relevance: These platforms are ideal for testing the $|v_{observer} - v_{group}|$ dependence by placing beam splitters or detectors on moving stages, since mechanical motion and Sagnac-type phases are routinely handled. Our visibility law can be fit against measured contrasts under controlled platform velocities.

6. CHALLENGING OR CONSTRAINING EXPERIMENTS

6.1. Quantitative Duality (Englert–Greenberger–Yasin)

Core observation: Inequalities relate visibility V and distinguishability D, e.g., $V^2 + D^2 \leq 1$. Experiments confirm that increasing which-path information reduces visibility according to these bounds, without appealing to relative velocity of observers per se.

Constraint: Our $|v_{observer} - v_{group}|$-dependent visibility should be interpretable as changing D via detector coupling or timing/bandwidth effects, to avoid conflict with these established relations. A direct claim that velocity alone collapses waves independent of information channels would be challenged by these results.

Numerical link: If detector motion changes effective integration time τ or spectral overlap η, one can model $D(\tau, \eta)$ and thereby $V(\tau, \eta)$. Fitting α in our exponential V law to measured D-dependence would align our framework with quantitative complementarity.

6.2. Asymmetric Beam Interference

Core observation: Duality relations hold in unequal path probabilities and slit widths; visibility depends on asymmetry but still obeys complementarity bounds. Experiments show robustness of wave–particle trade-offs in non-ideal geometries.

Constraint: Our transverse-spread thresholds must accommodate asymmetric illumination and nonuniform w. Replace w by an effective coherence aperture w_{eff} derived from mode profiles to remain consistent with these findings.

6.3. Bell Tests and Lorentz Invariance

Core observation: Loophole-free Bell tests show CHSH violations $S > 2$, consistent across frames; detector motion does not change fundamental correlation strengths when spacelike separation and fair sampling are ensured.

Constraint: Extensions of our hypothesis to entanglement must preserve Lorentz invariance of correlations, attributing any changes to local detection efficiency, timing windowing, or phase referencing rather than fundamental frame dependence. Model motion-induced timing skew and coincidence window effects, not correlation-altering physics.

7. DOUBLE SLIT EXPERIMENT

The double-slit experiment has long been considered the "mystery" of quantum mechanics [67, 68]. For over a century, the double-slit experiment has been described in paradoxical and anthropomorphic terms: electrons "know" when they are observed, they "interfere with themselves," or they are guided by a mysterious "probability cloud." These descriptions, while pedagogically vivid, have perpetuated confusion even among the most brilliant physicists.

In this work, we present a rigorous reinterpretation that shows interference is not a single-particle phenomenon but the collective behavior of a monoenergetic ensemble of indistinguishable entities. The ensemble is described by a coherent wave packet, which may split and interfere with itself, but this packet is not a single electron; it is a superposition of quantum states. The superposition carries different probability amplitudes for the allowed states, and the initial density matrix assigns nonzero weight only to the states that actually participate in the ensemble at a given moment. States with zero weight, although permitted by the Hilbert space, do not contribute to the physical state at that time. Collapse is reframed as decoherence induced by probe interactions or observer-relative motion, and duality is understood as a change of perspective between different experimental stages. We provide explicit mathematical thresholds, numerical examples, and a comparative analysis of supporting and challenging experiments. This framework demystifies the double-slit experiment while preserving consistency with relativity, decoherence theory, and experimental results.

In this paper, we argue that these mysteries dissolve when interference is understood as the behavior of a monoenergetic ensemble of indistinguishable particles, rather than as a property of a single particle. The ensemble is described by a coherent wave packet, which can split and interfere with itself, but this packet is not a single electron. The interference pattern is the statistical footprint of the ensemble's coherence, revealed only after many detections.

Interference requires phase coherence across the beam width w. If the phase variation exceeds one fringe period, interference is suppressed:

$$\Delta\phi \gtrsim 2\pi. \tag{33}$$

$$\Delta\phi \approx k\Delta\theta w = \frac{2\pi}{\lambda}\Delta\theta w \gtrsim 2\pi \quad \Rightarrow \quad \Delta\theta \gtrsim \frac{\lambda}{w}. \tag{34}$$

$$\Delta\phi \approx \frac{\Delta p_\perp w}{\hbar} \gtrsim 2\pi \quad \Rightarrow \quad \Delta p_\perp \gtrsim \frac{2\pi\hbar}{w} \quad \Rightarrow \quad \Delta v_\perp \gtrsim \frac{2\pi\hbar}{mw}. \tag{35}$$

Define the transverse coherence length:

$$\ell_c \sim \frac{\lambda}{\Delta\theta}. \tag{36}$$

Interference requires $\ell_c \gtrsim w$ [77, 79].

7.1. Double Slit Experiment: Historical Mysteries

1. "The electrons know if they are being looked at." Traditional mystery: This phrase comes from the fact that interference disappears when detectors are placed at the slits, as if the electron "senses" observation.

Our Framework reinterpretation: Placing a detector at a slit introduces a coupling that increases distinguishability D. In our language, this is equivalent to the detector's worldline intersecting the beam in such a way that relative motion and bandwidth reduce coherence. It's not that the electron "knows," but the act of seeing entails an input of probe signal which destroys the coherence of the group of monoenergetic particles, that the observer's position and response function alter the accessible coherence, reducing visibility V.

2. "The electron's wavepacket splits itself and each half goes through different slits. Traditional mystery that the wavefunction is often pictured as a literal wave dividing into two.

Our Framework reinterpretation: The group velocity v_{group} carries the packet as a whole, but coherence across the slits allows the superposition $\Psi_1 + \Psi_2$. The "splitting" is not a physical division of a particle, but the phase-coherent overlap of the beam across both apertures. If transverse coherence length $l_c \geqslant d$ (slit separation), interference emerges; if not, the "split" picture fails.

3. "The electrons know the others have gone through the other slits, so they must go through the other slit." Traditional mystery: This anthropomorphic phrasing suggests electrons coordinate with each other.

Our Framework reinterpretation: Interference is not a single-particle phenomenon: each electron part of the group of electrons in the beam interferes with other parts, provided coherence is preserved, will result in an interference pattern at the detector. The apparent "knowledge" is just the statistical buildup of fringes from many independent detections. In our framework, the detector's relative motion (non-zero relative velocity) with the entities, determines a particle behaviour or individual electron detections and their accumulation in time results into a visible interference pattern (wave-like) while individula detections remain localized (particle-like).

4. "There is a probability cloud guiding electrons and gives them their wave behavior." is another Traditional mystery. This is the Born rule interpretation: $\mid \Psi \mid^2$ is a probability density.

Our Framework reinterpretation: The "cloud" is the probability current J^μ, which in co-moving frames aligns with wave propagation. In non-co-moving frames, the current appears localized, giving particle-like detection. Thus, the "cloud" is not a mysterious guiding entity, but the frame-dependent manifestation of the wavefunction's coherence.

5. "The act of measurement collapses the wavefunction." A Traditional mystery in which the Collapse is often treated as instantaneous and inexplicable.

Our Framework reinterpretation: Collapse is rephrased as decoherence: off-diagonal terms in the density matrix vanish when $\triangle p_\perp \omega \frac{\omega}{\hbar} \geqslant 2\pi$ or when $\mid v_{observer} - v_{group} \mid$ increases distinguishability. Measurement is simply the detector's worldline interacting with the beam, reshaping coherence. Individual electrons are singled out (detectected out) of the previously coherent monoenergetic indistinguishable group of particles. The sum total of these detection readings in time correspond to complete measurement of the entity.

6. "The interference pattern disappears if we try to find which slit the electron went through." This Traditional mystery is the essence of complementarity.

Our Framework reinterpretation: Which-path detection introduces transverse momentum kicks ($\triangle p \perp$) or timing tags, reducing coherence length l_c. In our model, this is equivalent to increasing $\triangle v_{\perp}$ or altering the observer's effective sampling kernel, which suppresses interference.

7. "Each electron interferes with itself." This Traditional mystery phrase is paradoxical if only one thinks of electrons as indivisible particles. The phrase is shorthand for saying the wavefunction amplitude spans both slits, and the probability current interferes.

Our Framework reinterpretation: This phrase is simply the case where $v_{observer} = v_{group}$ and $l_c \geqslant d$, so coherence is preserved across both paths.

8. "Observation creates reality." This Traditional mystery is a philosophical extrapolation of the statement saying the act of looking determines the outcome.

Our Framework reinterpretation the Observation corresponds to the detector's spacetime world-line trajectory and coupling with the quantum entity. What is "created" is not reality itself, but the operationally accessible subset of the wavefunction, filtered by the observer's relative frame and apparatus.

9. Other historical metaphors worth noting "Pilot wave guides the particle" (de Broglie–Bohm): In our framework, the guiding wave is reinterpreted as the coherence structure of the beam, modulated by observer motion. "Collapse is instantaneous and nonlocal": In our framework, collapse is replaced by decoherence rates tied to $\triangle v_{\perp}$ and $\mid v_{observer} - v_{group} \mid$, which are local and operational. "Electrons behave differently when watched": In our framework, "watching" = introducing couplings that reduce coherence.

Synthesis: Our framework demystifies these historical paradoxes by replacing the anthropomorphic language ("electrons know") with operational criteria (coherence length, relative velocity, detector response). Showing that "collapse" is not metaphysical, but as the result of the loss of phase coherence due to transverse/longitudinal spread of the group velocity of the entities, the observer/detector's theoretically assumed relative motion, or the external influences. Embedding the whole story in relativistic covariance: probabilities and currents transform consistently, and only detector coupling changes outcomes.

7.2. Ensemble Interpretation of Interference

Conventional explanation is that a single-particle interferes with itself. The wavefunction is said to split at the slits, traverse both paths, and recombine at the screen. This is infered from experiments where interference pattern emerges even when electrons are sent one at a time, so the explanation is framed as a single-particle phenomenon.

Collapse by measurement: If a detector is placed at a slit, the wavefunction "collapses" into one path, destroying interference. This is often described as the electron "knowing" it is being observed.

Probability cloud: The Born rule is invoked:$\mid \Psi \mid^2$ is a probability density, interpreted as a "cloud" guiding the likelihood of detection.

Our Framework (Group-Based, Relational, Observer-Relative) Not single-particle interference: In our view, the interference is not a mystical self-interference of one particle. Instead, it is the collective behavior of a monoenergetic ensemble of indistinguishable electrons. The beam is coherent as a group before the slits. At the slits, the beam is divided into two coherent sub-ensembles. After the slits, the phase difference between these sub-ensembles produces the interference pattern. Each detection event is a random sample from the ensemble distribution, but the pattern emerges only from the group statistics. Probe signals destroy coherence: The act of "looking" is not mystical. It requires a probe signal (photon, field, etc.), which injects energy and momentum into the system. This breaks the monoenergetic condition of the ensemble, increases $\triangle v_{\perp}$, and thereby destroys coherence.

In our language: the probe increases transverse spread or alters the sampling kernel, reducing visibility V. This is why interference disappears when detectors are placed at the slits. Cloud as group behavior: The "probability cloud" is not an ethereal guiding field, but the statistical manifestation of the group's coherent density distribution. The cloud is the ensemble's behavior, not a property of a single electron. Collapse as perspective change: Physically, the beam simply propagates from source to detector. Collapse is not a physical discontinuity but an implicit change in the observer's perspective: from describing the ensemble as a coherent wave (before detection) to describing it as localized impacts (after detection). Instantaneity and nonlocality are artifacts of this implicit perspective shift, not physical signals propagating faster than light.

How This Reframes the Historical "Mysteries" "Electrons know if they are being looked at" → No, the probe signal injects energy, breaking coherence. "Each electron interferes with itself" → No, the ensemble interferes with itself; indistinguishability makes it appear as if one electron does. "Probability cloud guides electrons" → The cloud is the group's coherent density, not a guiding field. "Collapse is instantaneous and nonlocal" → Collapse is a theoretical re-description when the observer shifts from ensemble coherence to detection outcomes. "Observation creates reality" → Observation filters which subset of the ensemble's coherence is operationally accessible.

Our framework restores physical realism: interference is a property of the ensemble, not a paradoxical self-action of a single particle. Grounds "collapse" in decoherence and observer perspective, not metaphysical discontinuities. Explains why monoenergetic, indistinguishable ensembles are essential: they allow coherence to persist across the slits. Provides a relational, observer-relative reinterpretation that is consistent with relativity and decoherence theory. This is a powerful way to demystify the double-slit experiment. Instead of anthropomorphic metaphors, we give a mechanistic account: coherence is a group property, destroyed by probe interactions, and duality is a matter of relational observer perspective.

The standard narrative claims that “each electron interferes with itself.” The wavefunction is pictured as splitting at the slits and recombining at the screen. This leads to paradoxical imagery of indivisible particles being in two places at once.

Ensemble vs. Single-Particle Interference Conventional narrative: The double-slit experiment is often described as “a single electron interferes with itself.” The wavefunction is pictured as a single particle’s probability amplitude splitting at the slits and recombining. This leads to the paradoxical imagery: how can one indivisible particle be in two places at once?

Our reinterpretation: The interference is not a mystical property of a lone electron. It is the collective behavior of a monoenergetic ensemble of indistinguishable electrons. The ensemble can be represented mathematically as a wave packet: a superposition of momentum states centered around a common group velocity. This packet is not “one electron,” but the statistical state of the entire group. When the packet encounters the slits, it is divided into two coherent sub-packets. These sub-packets interfere with each other downstream, provided coherence is preserved. Each detection event is a random sample from the ensemble distribution, but the interference pattern emerges only after many detections — the sum total of all possible detector readings.

Why the “self-interference” picture is misleading: Saying “the packet splits and interferes with itself” is acceptable only if we remember that the packet is an ensemble description, not a single electron. The mystery arises when the packet is reified as a single particle. In reality: No single electron ever interferes with itself. The interference pattern is the statistical footprint of the group’s coherence. The indistinguishability of the electrons makes it impossible to track “which one went where,” so the group behaves as a coherent whole.

In contrast, interference is the collective behavior of a monoenergetic ensemble of indistinguishable electrons: The ensemble is described by a wave packet, a superposition of momentum states centered around a group velocity. The packet is not a single electron, but the statistical state of the group. At the slits, the packet divides into two coherent sub-packets, which interfere downstream. Each detection is a random sample, but the interference pattern emerges only after many detections.

Thus, while one may say the “packet interferes with itself,” it must be remembered that the packet represents the ensemble, not an individual electron. The apparent self-interference of a single particle is an artifact of treating the ensemble description as if it were an individual trajectory.

- *“Electrons know if they are being looked at.”* Looking entails a probe signal, injecting energy and destroying the monoenergetic condition. This increases $\Delta v_\perp$ and destroys coherence.

- *“Each electron interferes with itself.”* No, the ensemble interferes with itself. The packet is not a single electron.

- *“Probability cloud guides electrons.”* The cloud is the collective density distribution of the ensemble, not a guiding field.

- *“Collapse is instantaneous and nonlocal.”* Collapse is a change in observer perspective: from ensemble coherence to localized detections. Physically, the beam propagates continuously; only the description changes.

- *“Observation creates reality.”* Observation filters which subset of the ensemble’s coherence is operationally accessible.

Experiment System Key Observable Relevance

Davisson–Germer (1927) [69] Electrons Bragg peaks Establishes de Broglie scaling, coherence requirements

Tonomura (1989) [70] Electrons Single-electron fringes Ensemble statistics build interference

Quantum eraser [71, 72] Photons Conditional fringes Visibility depends on information channels
Wheeler delayed choice [73, 74] Photons Late-choice outcome Supports observer-relative framing

Arndt (1999) [75] C_{60} Molecular fringes Universality, decoherence scaling

Atom/neutron interferometry [77] Atoms, neutrons Phase shifts Tests coherence vs. apparatus motion

Englert inequality [80] Photons V–D tradeoff Confirms complementarity quantitatively

Bell tests [81, 82] Photons, ions CHSH violation Lorentz-invariant correlations

7.3. Proposed Macroscopic Ensemble Interference with Classical Entities

Conventionally, the double-slit experiment is said to apply only to quantum entities (electrons, photons, atoms), not to classical macroscopic objects like cannonballs, primarily because the de Broglie wavelength of a single macroscopic object is extraordinarily small. Here, based on ensemble-coherence principles discussed earlier, we propose an experiment to reveal interference-like effects for macroscopic classical entities by treating them not as isolated single bodies but as a monoenergetic ensemble of identical, indistinguishable entities that share a group velocity and can be characterized by a group coherence length and an effective group wavelength in terms of spatial phase ordering.

- *Not single-particle interference:* We consider a coherent ensemble ("large balls") that propagates inertially with minimal transverse and longitudinal velocity spread, preserving phase ordering.

- *Smooth splitting into sub-ensembles:* The ensemble passes through two regions (wide "slits" or channels) that divide the group without destroying coherence. Splitting is enacted by a smooth gradient (e.g., airflow field, wind nozzles, fluidized medium).

- *Controlled path difference:* A deterministic gradient induces a controlled path difference. Downstream overlap produces interference-like density modulation analogous to fringes.

8. OPERATIONAL DEFINITIONS FOR A MACROSCOPIC ENSEMBLE

- *Group velocity:* v_{group} — mean velocity of the ensemble center-of-mass flow.

- *Velocity spreads:* $\Delta v_\parallel$ and $\Delta v_\perp$ — longitudinal and transverse spreads. Coherence requires both to be small compared to v_{group}.

- *Phase ordering field:* A spatially smooth external field (e.g., aerodynamic, vibrational, conveyor phasing) that defines phase across the beam cross-section.

- *Effective group coherence length:* l_c — transverse distance over which phase ordering persists. Requires $l_c \gtrsim w$.

- *Effective group wavelength:* λ_{eff} — spatial periodicity in phase ordering, e.g., induced by periodic forcing or timing modulation.

9. DECOHERENCE THRESHOLDS IN MACROSCOPIC REGIME

Structural conditions suppressing quantum interference apply to classical ensembles via operational analogs:

$$\Delta\phi \approx k_{\text{eff}}\Delta\theta w = \frac{2\pi\Delta\theta w}{\lambda_{\text{eff}}} \gtrsim 2\pi \Rightarrow \Delta\theta \gtrsim \frac{\lambda_{\text{eff}}}{w}$$

$$\Delta\phi \approx \frac{\Delta p_\perp w}{\hbar_{\text{op}}} \gtrsim 2\pi \Rightarrow \Delta v_\perp \gtrsim \frac{2\pi\hbar_{\text{op}}}{mw}$$

Here, $\hbar_{\text{op}}$ is a formal scale parameter capturing phase rigidity. It is not Planck's constant. Coherence is lost when $\Delta v_\perp$ exceeds the threshold set by the phase-ordering protocol.

Define transverse coherence length:

$$l_c \sim \frac{\lambda_{\text{eff}}}{\Delta\theta}, \quad \text{require } l_c \gtrsim w$$

10. EXPERIMENTAL DESIGN CONCEPT

- *Source:* Feeder line produces identical spheres with narrow velocity distribution: $\Delta v_\parallel/v_{\text{group}} \ll 10^{-3}$, $\Delta v_\perp/v_{\text{group}} \ll 10^{-6}$.

- *Splitter regions:* Two wide channels with gradient fields (e.g., laminar air flows) that smoothly deflect the ensemble into sub-ensembles.

- *Phase ordering:* Imposed via synchronized vibration or airflow modulation at frequency f, yielding $\lambda_{\text{eff}} = v_{\text{group}}/f$.

- *Detection plane:* Downstream array (camera, sensors) at distance L images spatial density of impacts.

$$s \approx \frac{\lambda_{\text{eff}} L}{d}, \quad V \sim \exp\left(-\frac{w^2}{l_c^2}\right)$$

11. PRACTICAL CONSTRAINTS AND TOLERANCES

- *Angular divergence:* Require $\Delta\theta \lesssim \lambda_{\text{eff}}/w$

- *Velocity spreads:* For $m \sim 0.1$–1 kg and $v_{\text{group}} \sim 1$–5 m/s, target $\Delta v_\perp \lesssim 10^{-3}$–$10^{-2}$ m/s

- *Phase stability:* Modulation f must be phase-locked across channels to within $\sim 1^\circ$

- *Gentle splitting:* Use smooth aerodynamic fields; avoid turbulence or granular collisions

This macroscopic experiment does not rely on the quantum de Broglie wavelength of individual balls. Instead, it exploits:

1. Ensemble coherence (phase ordering of the group)

2. Smooth splitting into two sub-ensembles

3. Controlled path difference yielding phase differences

4. Downstream overlap producing density modulation analogous to interference fringes

Under these conditions, the observed modulation is operationally equivalent to interference patterns in quantum beams, because the same coherence criteria apply:

$$l_c \gtrsim w, \quad \Delta\theta \lesssim \frac{\lambda_{\text{eff}}}{w}$$

Visibility V is set by transverse spread and phase-ordering fidelity. The crucial point is that interference is a group phenomenon; by constructing a macroscopic ensemble with engineered phase coherence, we can reproduce interference-like signatures without invoking single-particle quantum behavior.

This proposal mirrors established quantum interferometry logic:

- *Coherence length and visibility:* The macroscopic visibility $V(w) \sim \exp\left[-(w/l_c)^2\right]$ parallels electron and atom interferometer visibility laws.
- *Decoherence channels:* Random kicks, turbulence, and timing jitter act as macroscopic analogs of environmental decoherence, increasing effective $\Delta v_\perp$ and diminishing l_c.
- *Ensemble statistics:* As with single-electron double-slit build-up, a clear modulation emerges statistically after many impacts, not from a single trajectory.

11.1. Numerical Sketch

Let $v_{\text{group}} = 2.0$ m/s and modulation frequency $f = 2$ Hz. Then:

$$\lambda_{\text{eff}} = \frac{v_{\text{group}}}{f} = 1 \text{ m}$$

Take splitter spacing $d = 0.5$ m and detection distance $L = 10$ m:

$$s = \frac{\lambda_{\text{eff}} L}{d} = \frac{1 \cdot 10}{0.5} = 20 \text{ m}$$

To obtain a practical s (e.g., tens of cm to meters), increase f or reduce L/d. For $f = 20$ Hz ($\lambda_{\text{eff}} = 0.1$ m), $d = 0.5$ m, $L = 5$ m:

$$s = \frac{0.1 \cdot 5}{0.5} = 1 \text{ m}$$

Impose:

$$\Delta\theta \lesssim \frac{\lambda_{\text{eff}}}{w}$$

With $w = 0.1$ m and $\lambda_{\text{eff}} = 0.1$ m, this implies $\Delta\theta \lesssim 1$ rad (loose). For sharp fringes, tighten to $\Delta\theta \lesssim 10^{-2}$–$10^{-3}$ rad via flow straighteners and phase-locking. This increases l_c and V.

- This is an operational analog of interference, not quantum de Broglie interference of single macroscopic objects. It tests the thesis that interference is fundamentally a coherence-of-ensemble phenomenon.
- Success hinges on engineering phase ordering and maintaining ultra-low velocity spreads. The experiment bridges statistical physics, fluid dynamics, and interferometry.
- A positive result would underscore that the "mystery" of the double-slit is not about single particles, but about coherence, phase, and ensemble indistinguishability—concepts that transcend the quantum/classical divide when implemented operationally.

12. EXPERIMENTAL PROGRAM: ELECTRON GUN ARRAY WITH VELOCITY CONTROL AND ELECTROMAGNETIC SLIT ANALOGS

We propose a controllable, modular platform to probe interference as a function of:

1. Transverse and longitudinal velocity spreads
2. Field-defined "slits" via electromagnetic (EM) structures

The apparatus decouples geometric aperture effects from kinematic and field-induced phase control, enabling precise tests of visibility V versus $\Delta v_\perp$, $\Delta v_\parallel$, and effective slit parameters (field strength, gradient, and extent). This directly interrogates the ensemble-coherence thesis and quantifies thresholds predicted by:

$$V \approx V_0 \exp\left(-\frac{\Delta v_\perp w}{\lambda}\right), \quad \Delta\theta \gtrsim \frac{\lambda}{w}, \quad l_c \gtrsim w$$

and the momentum–field relation:

$$\Delta p_\perp \approx qBL$$

12.1. Array of Electron Guns and Velocity Control

An array ($N = 8$–32) of independently tunable electron guns produces quasi-parallel beams with adjustable kinetic energies and emittance. Each gun is paired with:

- Electrostatic lenses (Einzel lenses) for longitudinal velocity tuning ($v_\parallel$) and energy spread minimization (ΔE)
- Magnetic/electrostatic deflectors for transverse velocity control ($\Delta v_\perp$)

- Adjustable collimators to set beam width w and angular divergence $\Delta\theta$

Control parameters for each beam i:

$$(v_\parallel)_i, \quad (\Delta v_\parallel)_i, \quad (\Delta v_\perp)_i, \quad w_i, \quad \Delta\theta_i$$

Scan protocols:

1. Transverse scans: Fix E and w, vary $\Delta v_\perp$ in fine steps (e.g., 1–50 m/s) to map $V(\Delta v_\perp)$
2. Longitudinal scans: Fix $\Delta v_\perp$ and w, vary E (and hence λ) to map $V(\lambda)$ and fringe spacing $s = \lambda L/d$
3. Mixed scans: Joint variation of $(\Delta v_\perp, \Delta v_\parallel)$ to quantify longitudinal dephasing vs transverse washout

12.2. Electromagnetic Field "Slits"

Instead of mechanical apertures, define two spatially separated interaction regions using EM fields:

a. Magnetic slit analogs (Lorentz deflection): Two narrow, uniform-B regions of length L_B and width w_B impart transverse momentum:

$$\Delta p_\perp = qBL_B, \quad \Delta\theta \approx \frac{\Delta p_\perp}{p} = \frac{qBL_B}{p}$$

b. Electrostatic slit analogs (phase plates): Two thin electrostatic phase regions with potential $V(x)$ imprint differential phases:

$$\Delta\phi(x) = \frac{1}{\hbar}\int \frac{eV(x)}{v_\parallel}\,dz$$

Field scans vary B or V to tune:

- Path separation $d(B)$
- Phase difference $\Delta\phi(V)$
- Effective aperture $w_{\text{eff}}(B, V)$

Target collapse threshold for magnetic case:

$$qB_cL_B \gtrsim \frac{2\pi\hbar}{w}$$

12.3. Interference Geometry and Detection

Place a detection plane at distance L from the slit analogs. For two-beam interference:

$$s = \frac{\lambda L}{d}, \quad V \sim \exp\left(-\frac{w^2}{l_c^2}\right), \quad l_c \sim \frac{\lambda}{\Delta\theta}$$

Use high-sensitivity CCD/MCP detectors; integrate single-event impacts to recover ensemble fringes.

a. Measurement protocol:

1. Calibrate $\lambda(E)$, $p(E)$, $\Delta\theta(\Delta v_\perp)$ via diagnostics
2. Record V vs $\Delta v_\perp$ at fixed (E, w, d, L)
3. Record V vs $\langle B\rangle$ and $\langle V\rangle$ for EM slit analogs
4. Extract l_c from $V(w)$ fits and compare to $l_c \sim \lambda/\Delta\theta$
5. Verify threshold $qBL_B \approx 2\pi\hbar/w$ where visibility collapses

12.4. Expected Relations and Tests

a. Transverse velocity spread dependence:

$$V(\Delta v_\perp) \approx V_0 \exp\left(-\frac{\Delta v_\perp w}{\lambda}\right)$$

b. Field-induced collapse:

$$qB_cL_B \gtrsim \frac{2\pi\hbar}{w} \Rightarrow B_c \gtrsim \frac{2\pi\hbar}{qwL_B}$$

c. Fringe spacing validation:

$$s = \frac{\lambda L}{d}, \quad V(d, w) \text{ benchmarks } w_{\text{eff}}(B, V)$$

12.5. Numerical Illustration

1. *Calculate de Broglie wavelength:* Electron momentum:

$$p = \sqrt{2m_eE}.$$

With $m_e = 9.11 \times 10^{-31}$ kg, $E = 50\,\text{keV} = 8.0 \times 10^{-15}$ J:

$$p = \sqrt{2 \cdot 9.11 \times 10^{-31} \cdot 8.0 \times 10^{-15}} \approx 1.2{\times}10^{-22}\text{ kg m/s}.$$

Wavelength:

$$\lambda = \frac{h}{p} \approx \frac{6.63 \times 10^{-34}}{1.2 \times 10^{-22}} \approx 5.5 \times 10^{-12}\,\text{m}.$$

2. *Choose beam width:* Let $w = 10\,\mu\text{m} = 1.0{\times}10^{-5}$ m.
3. *Angular threshold:*

$$\Delta\theta \gtrsim \frac{\lambda}{w} = \frac{5.5 \times 10^{-12}}{1.0 \times 10^{-5}} = 5.5 \times 10^{-7}\,\text{rad}.$$

So if the beam divergence exceeds about half a microradian, fringes vanish.

4. *Momentum spread threshold:*

$$\Delta p_\perp \gtrsim \frac{2\pi\hbar}{w} = \frac{2\pi \cdot 1.05 \times 10^{-34}}{1.0 \times 10^{-5}} \approx 6.6 \times 10^{-29}\,\text{kg m/s}.$$

5. *Velocity spread threshold:*

$$\Delta v_\perp \gtrsim \frac{\Delta p_\perp}{m_e} = \frac{6.6 \times 10^{-29}}{9.11 \times 10^{-31}} \approx 72\,\text{m/s}.$$

So if the transverse velocity spread exceeds ~ 70 m/s, interference is lost.

Interpretation: For 50 keV electrons, the longitudinal velocity is about $v \sim 1.3 \times 10^8$ m/s. The transverse velocity spread must be less than $\sim 10^{-6}$ of this value to preserve interference. This illustrates why extreme collimation is required in electron interferometry: even tiny angular spreads can destroy coherence [70, 77].

Consider 50 keV electrons:

$$\lambda \approx 5.5 \times 10^{-12}\ \text{m}, \quad p \approx 1.2 \times 10^{-22}\ \text{kg m/s}$$

Let $w = 10\,\mu\text{m}$, $d = 1\,\mu\text{m}$, $L = 1$ m:

$$s = \frac{\lambda L}{d} \approx 5.5\ \text{mm}$$

Transverse spread threshold:

$$\Delta v_\perp \gtrsim \frac{w \cdot p}{m} \approx 72\ \text{m/s}$$

Thus, transverse velocity spread must be less than 10^{-6} of the longitudinal velocity ($\sim 10^8$ m/s) to preserve interference [70].

Part II

13. TWO ICONIC EXPERIMENTS: DAVISSON–GERMER AND MERLI–MISSIROLI–POZZI

13.1. Davisson–Germer Experiment and Its Implications

The Davisson and Germer experiment performed in 1927[69] is commonly cited as the original experiment belonging to a general class of so-called double path experiments, widely known as double slit experiments. In such experiments a coherent beam of an entity is split into two separate beams that later combine into a single beam. Changes in the path length of both beams result in a phase shift, creating an interference pattern, a result that would not be expected if the entity consisted of classical particles. The interference pattern is observed due to variation in density of the particles hitting the detector screen. Any attempt at detection of particle path through either of the slits destroys the interference pattern. A single entity, whether photon or electron, appears to produce the interference pattern in the form of dark and light bands, even though the individual hits on the detector screen seem to be discrete points randomly distributed across the detector screen over time. Closing any one of the slits will destroy the interference pattern, indicating the need for dual path for the interference. These apparently contradictory experimental facts have remained perplexing and a source of intrigue for over a century.

Davisson and Germer investigated the interaction between a beam of electrons and a crystal of nickel, by directing a beam of electrons against a {111}-face of a crystal at various angles of incidence. They measured the intensity of scattering in the incidence plane as a function of bombarding potential and direction. They found that under certain conditions a sharply defined beam of scattered electrons was issued from the crystal in the direction of regular reflection.

These sharp beams occurred whenever the speed of the incident electrons was within certain ranges which peaked at certain locations, not only as the angle of incidence was varied, but also as the bombarding potential was varied. Their interpretation was that the incident beam of electrons of speed v was equivalent to a beam of waves of wavelength $\lambda = \frac{h}{mv}$, a portion of the incident beam being regularly reflected through the process of coherent scattering from each of the layers of atoms lying parallel to the crystal face. The intensity of this resultant beam was a maximum when the elementary beams proceeding from individual layers emerged from the crystal in phase. The condition for such a maximum in the case of X-ray reflection was that the wavelength and the angle of the incident beam be related to the separation between successive atom layers of the crystal through the Bragg formula $n\lambda = 2d\cos\theta$. The condition in the case of electron reflection was somewhat different. The wavelength $\lambda = \frac{h}{mv}$ of the reflected beam at the maximum intensity was not given by the Bragg formula. However, what was important was not these differences between the electrons and X-ray phenomena, but rather the actual distribution in angle of electrons of all speeds issuing from a {111}-face of a nickel crystal at various angles of incidence and the speeds of bombardments, which peaked intensity at sharp spurs.

These sharp spurs characterized the reflected beam of electrons with least velocity distribution at one or another of the intensity maxima. The axes of these spurs lay accurately in the direction of the regular reflection. The angles of incidence θ_1 and reflection θ_2 were in all cases the same to within half a degree within the limit of uncertainty in their measurements. The least velocity distribution indicates same velocity, or monoenergetic character of the electron group in the beam of electrons.

In their data they plotted the intensity of the reflected beam for angle of incidence 10° against the square root of the bombarding potential. The incident electrons at angle θ_1 were reflected by the crystal atoms at angles θ_2, after collision at various layers of crystal. The reflected electrons would produce a peak when the reflected electrons from different layers of atoms were in phase.

The phase of electrons would be the only distinguishing parameter between the incident and reflected electrons. It is clear from the above that even though they did not intend to investigate the wave nature of the electrons or indeed electron interference, they confirmed the de Broglie relationship

$$\lambda = \frac{h}{\sqrt{2mE}}.$$

Analogously, it is claimed here that in addition to the above, they have unintentionally shown that a necessary condition for the electron's interference pattern is their uniform or least velocity distribution. The Davisson–Germer Experimental results not only showed a wave behavior and interference, also included overwhelming evidence for the reason why the electrons show a wave behavior and interference. These evidence lead to an alternative and more logical interpretation of the wave–particle duality behavior of matter and radiation.

13.2. Davisson–Germer: quantitative dependence on longitudinal and transverse velocities

We parameterize the electron beam by longitudinal speed $v_\parallel = \sqrt{2eV/m_e}$ and transverse divergence $\sigma_\theta \simeq v_\perp/v_\parallel$. The de Broglie wavelength is $\lambda(\mathrm{nm}) \approx 1.226/\sqrt{V(\mathrm{eV})}$, and the Ni(111) Bragg angle obeys $\sin\theta = \lambda/(2d)$ with $d = 0.091\,\mathrm{nm}$.

TABLE I. Energy dependence of λ, $v_\parallel$, and predicted Ni(111) peak angle.

V (eV)	λ (nm)	$v_\parallel$ (10^6 m/s)	$\sin\theta$	θ (deg)
40	0.194	3.74	1.066	no 1st-order peak
48	0.177	4.11	0.973	77.8
54	0.167	4.34	0.918	66.7
60	0.158	4.58	0.868	60.2
68	0.149	4.86	0.819	55.0
75	0.142	5.10	0.780	51.3

Energy spread δV induces $\delta\lambda/\lambda \simeq \frac{1}{2}\delta V/V$, which broadens the peak by $\delta\theta_\parallel \simeq (\partial\theta/\partial\lambda)\,\delta\lambda$, with $\partial\theta/\partial\lambda = [2d\cos\theta]^{-1}$. The corresponding visibility reduction is

$$V_\parallel \approx \exp\left[-\left(\frac{\delta\theta_\parallel}{\Delta\theta_{\mathrm{res}}}\right)^2\right].$$

Transverse divergence σ_θ broadens the peak and reduces height according to

$$\mathrm{FWHM}_{\mathrm{obs}} \approx \sqrt{\mathrm{FWHM}^2_{\mathrm{crystal}} + (2\sqrt{2\ln 2}\,\sigma_\theta)^2}$$

,

$$V_\perp \approx \frac{1}{\sqrt{1+(\sigma_\theta/\sigma_{\mathrm{acc}})^2}}.$$

Assuming independent contributions, the observed contrast is

$$V_{\mathrm{tot}} \approx V_0\, V_\parallel\, V_\perp.$$

a. Example (54 eV). With $\theta \simeq 66.7°$ and $\delta V/V = 1\%$, we find $\delta\theta_\parallel \approx 0.68°$. For $\sigma_\theta \approx 0.85°$ and $\sigma_{\mathrm{acc}} \approx 0.5°$, one obtains $V_\parallel \approx 0.63$, $V_\perp \approx 0.51$, and $V_{\mathrm{tot}} \approx 0.32\,V_0$.

Peak position, height, and width vs longitudinal/transverse velocities

b. Longitudinal dependence (energy spread). $\lambda(V) = \frac{h}{\sqrt{2m_e eV}}$, $\frac{\delta\lambda}{\lambda} \simeq \frac{1}{2}\frac{\delta V}{V}$. $\frac{\partial\theta}{\partial\lambda} = \frac{1}{2d\cos\theta}$. $\delta\theta_\parallel \simeq \frac{1}{2d\cos\theta}\,\delta\lambda$.
Numerical at 54 eV: $\lambda = 0.1669$ nm, $\theta = 66.78°$, $\cos\theta = 0.394$.
$\frac{\partial\theta}{\partial\lambda} = \frac{1}{(0.182\ \mathrm{nm})\cdot 0.394} = 14.23$ rad/nm.
$\delta V/V = 1\% \Rightarrow \delta\lambda = 0.5\% \times 0.1669 = 8.35\times10^{-4}$ nm.
$\delta\theta_\parallel \approx 14.23 \times 8.35\times10^{-4} = 0.0119$ rad $= 0.68°$.
c. Transverse dependence (beam divergence).
$\sigma_\theta \simeq v_\perp/v_\parallel$,
$\mathrm{FWHM}_{\mathrm{obs}} \approx \sqrt{\mathrm{FWHM}^2_{\mathrm{crystal}} + (2\sqrt{2\ln 2}\,\sigma_\theta)^2}$.
$V_\perp \approx \frac{1}{\sqrt{1+(\sigma_\theta/\sigma_{\mathrm{acc}})^2}}$.
Numerical at 54 eV: $v_\parallel = 4.363\times10^6$ m/s.
Beam divergence 2° (rms $\sigma_\theta = 0.85° = 0.0148$ rad) $\Rightarrow$ $v_\perp \approx 0.0148\,v_\parallel = 6.46\times10^4$ m/s.
If $\sigma_{\mathrm{acc}} = 0.5° = 0.00873$ rad,
$V_\perp \approx 1/\sqrt{1+(0.0148/0.00873)^2} = 0.51$.

13.3. The Merli–Missiroli–Pozzi MMP Experiment and Its Implications

The Merli–Missiroli–Pozzi MMP experiment of 1976, titled "On the Statistical Aspect of Electron Interference Phenomena,'[30] ' obtained an interference pattern with an electron microscope using an electron biprism. A very thin wire was placed perpendicular to the electron beam, and in between two plates at ground potential. When a potential was applied to the wire, the electron beam was split into two deflected components which would continuously arrive at the detector, one at a time, and be observed on a television monitor. The electrons emerged as if from an effective source S, or from combined virtual sources S_1 and S_2, diffracted by the biprism wire F when at potential V, and interfered inside the region W on the observation plane OP.

MMP showed that when an electron of charge e, mass m, and speed v_0 passes the biprism wire F at a distance x away from it, it will be deflected through an angle α given by

$$\alpha = 2\tan^{-1}\left(\frac{2eV}{mv_0^2} \cdot \frac{\ln R}{\sqrt{R^2 - x^2}\, x}\right).$$

Depending on the voltage V being positive or negative, the electrons will be deflected towards or away from the wire. This results in a non-localized interference pattern which spans the entire overlapping region. A fluorescent screen placed at OP, a distance b below the wire F, revealed fringes of width

$$W = \frac{2ab}{a+b-r}\left(\frac{a+b}{a}\alpha\right),$$

with $r = 2 \times 10^{-7}$ m, $\alpha = 5 \times 10^{-5}$ radians, $a = 10$ cm, $b = 24$ cm, yielding $W = 23 \times 10^{-6}$ m. The fringes built up over time as single electrons arrived, demonstrating that interference is not due to electron–electron interaction but to ensemble coherence.

MMP emphasized that the computed distribution of classical trajectories did not reproduce the observed fringes. Only by introducing de Broglie waves and treating the system as a Fresnel biprism could the fringes be explained. The separation of the two virtual sources was $d = 2\alpha a$, and the fringe periodicity was

$$\ell = \frac{\lambda(a+b)}{d}.$$

They rejected the idea that interference results from spatially distributed wave-like electrons, noting that if this were the case, fringe intensity would decrease with beam current. Instead, reducing the current simply reduced the number of electrons reaching the screen per unit time, without affecting fringe visibility. Thus, the fringes arose from deterministic phase relationships within a monoenergetic ensemble.

TABLE II. Electron biprism interference: accelerating voltage V, de Broglie wavelength λ, longitudinal velocity $v_\parallel$, and predicted fringe spacing Δx for $L = 1.0$ m and $d = 1.0$ μm.

V (keV)	λ (pm)	$v_\parallel$ (10^7 m/s)	d (μm)	Δx (μm)
20	8.66	8.39	1.0	8.66
40	6.13	11.9	1.0	6.13
50	5.50	13.3	1.0	5.50
75	4.48	16.3	1.0	4.48
100	3.88	18.9	1.0	3.88

14. ELECTRON BIPRISM INTERFEROMETER: TRAJECTORIES, FIELDS, AND COHERENCE CONDITIONS

14.1. Monoenergetic ensemble and kinematics

We model the beam as a monoenergetic ensemble with longitudinal speed

$$v_\parallel(V) = \sqrt{\frac{2eV}{m_e}}, \qquad \lambda(V) = \frac{h}{m_e v_\parallel} = \frac{h}{\sqrt{2m_e eV}}, \quad (37)$$

and a small transverse angular spread (divergence) $\Delta\theta$ set by entrance apertures (slits). Longitudinal velocity fixes the de Broglie wavelength; transverse velocity sets the source angular size $\Delta\theta$ and hence transverse coherence length

$$\ell_\perp \approx \frac{\lambda}{\Delta\theta}. \quad (38)$$

14.2. Electrostatic biprism as an amplitude divider

An ultra-fine, biased filament (biprism) produces a symmetric electrostatic field that deflects the two halves of the incoming beam toward each other. Linearizing the transverse deflection for small angles,

$$\alpha \;\approx\; \frac{e\,\mathcal{K}\,V_b}{m_e v_\parallel^2}, \quad (39)$$

where V_b is the biprism bias and $\mathcal{K}$ is a geometry factor determined by filament radius, electrode spacing, and working distance. The biprism acts as an amplitude divider: rays passing on opposite sides experience equal and opposite deflections $\pm\alpha$, creating two *virtual sources* separated by an effective distance

$$d \;\approx\; 2\,\alpha\,L_{\mathrm{pre}}, \quad (40)$$

with L_{pre} the distance from the biprism to the plane of virtual source formation (set by lens settings and instrument geometry). At a downstream screen (detector) located a distance L from the plane of overlap, the fringe spacing is

$$\Delta x \;=\; \frac{\lambda\,L}{d}. \quad (41)$$

Equations (39)–(41) connect the table's $V \mapsto \lambda$ entries to Δx via the biprism geometry and bias.

14.3. Trajectory fixation and field-induced phase

Within the ensemble, each electron follows a spacetime trajectory fixed by $(v_\parallel, v_\perp)$ and the biprism field $\mathbf{E} = -\nabla\Phi$. The transverse equation of motion (small-angle) yields the deflection α in Eq. (39). The quantum phase accrued along a trajectory is

$$\phi \;=\; \frac{1}{\hbar}\int \Big(\tfrac{1}{2}m_e v^2 - e\,\Phi\Big)\,dt. \tag{42}$$

For a symmetric biprism field, the two arms acquire equal kinetic phases and opposite electrostatic phases with net differential phase $\Delta\phi$ proportional to V_b and the exact ray geometry. After linear optics re-imaging to the overlap plane, the superposed amplitudes produce fringes with spacing Δx in Eq. (41). Thus, once $(V, V_b, \mathcal{K}, L_{\rm pre}, L)$ and the entrance angular spread are set, both trajectories and phase are fixed operationally.

14.4. Role of slits and "influence of slit atoms"

Entrance slits (and their atomic-scale edges) set the transverse mode and angular spread $\Delta\theta$:

$$\Delta\theta \simeq \frac{a}{f_{\rm eff}}, \quad \ell_\perp \approx \frac{\lambda}{\Delta\theta}, \tag{43}$$

where a is the effective source size after collimation and $f_{\rm eff}$ denotes the instrument's effective focal length to the biprism. Edge roughness and microscopic fields near slit atoms can add small, static phase offsets; operationally, these are absorbed into the mode transfer function $A(\mathbf{r})$ and only affect visibility via mode mismatch. Mechanical and electrostatic stability of the slits preserves $\Delta\theta$ and avoids time-dependent phase noise.

14.5. Coherence maintenance from source to detector

Coherence is maintained if:

- *Longitudinal condition:* The path difference ΔL remains below the longitudinal coherence length $\ell_c \approx v_\parallel \tau_c$ (source bandwidth τ_c), i.e. $\Delta L \lesssim \ell_c$.
- *Transverse condition:* The virtual source separation d does not exceed the transverse coherence length, $d \lesssim \ell_\perp = \lambda/\Delta\theta$.
- *Field symmetry and stability:* The biprism bias V_b and geometry are stable so that opposite deflections $\pm\alpha$ are matched and the differential phase $\Delta\phi$ is stationary over the ensemble.
- *Overlap and mode matching:* The overlapping partial beams have high spatial overlap $\mathcal{O}$ at the detector; the observed visibility obeys

$$\mathcal{V} \;\approx\; \mathcal{V}_0\,\exp\!\Big[-\Big(\frac{d}{\ell_\perp}\Big)^2\Big]\,\exp\!\Big[-\Big(\frac{\Delta L}{\ell_c}\Big)^2\Big]\,\mathcal{O}, \tag{44}$$

  where $\mathcal{V}_0$ is the ideal contrast and $\mathcal{O} \in [0,1]$ quantifies cross-sectional mode overlap (set by beam waist versus acceptance).

These conditions translate the table's (V, λ) into operational predictions for Δx and $\mathcal{V}$ under specified $(V_b, d, L, \Delta\theta)$.

14.6. Numerical linkage to the table

For a fixed geometry ($L = 1.0\,\mathrm{m}$, $d = 1.0\,\mu\mathrm{m}$):

$$\Delta x(V) = \lambda(V)\,\frac{L}{d}, \qquad \lambda(V) \approx \frac{12.27\,\mathrm{pm}}{\sqrt{V\,(\mathrm{keV})}}. \tag{45}$$

Hence, the entries (20, 40, 50, 75, 100 keV) in the table map one-to-one to fringe spacings (8.66, 6.13, 5.50, 4.48, 3.88 μm). For a given entrance divergence $\Delta\theta$ (e.g., 10^{-5} rad), the transverse coherence length $\ell_\perp = \lambda/\Delta\theta$ dictates whether d must be reduced (by lowering V_b or adjusting $\mathcal{K}$) to preserve high visibility. Increasing V tightens λ and shrinks Δx, but it also increases $v_\parallel$, making the deflection angle $\alpha \propto V_b/v_\parallel^2$ smaller; maintaining a fixed d as V changes therefore requires compensating V_b according to Eq. (39).

14.7. Conditions for Interference and Final Synthesis

The Davisson–Germer and MMP experiments together reveal that interference requires angular dependence of phase shifts, coherent monoenergetic ensembles, phase-modulating structures such as crystals or wires, and fragility of coherence under measurement. The interference pattern is destroyed if the coherent superposition is disturbed. The synthesis is that interference arises from deterministic, phase-coherent ensembles, not from individual particles behaving as waves. Wave behavior is emergent, not intrinsic. Measurement collapses group coherence, not individual wavefunctions.

15. EXPERIMENTAL SUPPORT AND CHALLENGES

Historical and modern experiments support this ensemble interpretation. Davisson–Germer demonstrated coherent scattering of monoenergetic electrons from atomic layers, producing phase-dependent intensity peaks. MMP showed interference from single electrons arriving one at a time, ruling out electron–electron interaction and emphasizing the role of ensemble coherence. Later work by Bach et al. in 2013[40] , using a transmission electron microscope, confirmed that interference persists even when electrons are emitted individually, provided the beam coherence is maintained. This supports the idea that interference arises from indistinguishable, monoenergetic ensembles rather than intrinsic duality of single particles. Arrabal in 2025[43] proposed a Coulomb field modulation model, arguing that interference is a deterministic result of periodic Coulomb fields within slit materials, further reinforcing the ensemble interpretation. Schmid and Hommelhoff in 2020[45] surveyed electron interference in electric and magnetic fields, finding that interference patterns depended on external field configurations and beam coherence, not probabilistic behavior.

At the same time, some experiments present challenges or mixed evidence. Quantum eraser and delayed-choice experiments, such as those of Kim et al. in 2000[44] , showed that interference can be restored or destroyed retroactively depending on whether path information is available. These results challenge strict determinism and suggest contextual dependence of interference. Single-photon beam splitter experiments in optics also show interference even when photons are emitted with long time intervals. Some interpretations argue this supports intrinsic wave–particle duality, although coherence length and detector integration time may still imply ensemble-like behavior.

Taken together, these findings reinforce the central claim of this manuscript: interference arises from deterministic, phase-coherent ensembles of monoenergetic, indistinguishable particles, and not from intrinsic wave–particle duality of individual entities. The wave nature is emergent, not fundamental. Measurement collapses group coherence, not individual wavefunctions. This reinterpretation provides a physically grounded framework for understanding interference phenomena and opens the door to exploring interference in larger, macroscopic systems, provided they meet the criteria of monoenergetic coherence and indistinguishability.

15.1. Supporting Experiments and Ensemble Coherence

The single–electron buildup experiments by Tonomura and collaborators [70] are often treated as evidence for wave–particle duality; in fact, they are more compatible with the claim that interference arises from indistinguishable, monoenergetic ensembles. In those studies, electrons were emitted sparsely enough that, on average, one was present in the apparatus at a time, and the interference image accumulated gradually as detection events were registered. Reducing current lowered the rate of events but did not degrade fringe contrast, provided the source coherence and apparatus stability were maintained. This behavior is precisely what one expects if the pattern is governed by phase relations and indistinguishability within the ensemble over the apparatus coherence time, not by any intrinsic wave spread of each single electron.

Modern transmission electron microscope double–slit implementations [40] show the same logic at higher precision. In controlled TEM experiments, the electron beam is energy–filtered, collimated, and sent through nanofabricated slits, and interference persists down to regimes where the detector integrates single–electron hits. The decisive parameter is the coherence of the beam as determined by its energy spread and transverse emittance. When the energy spread is narrowed and the transverse coherence length

$$L_c \approx \frac{\hbar}{\Delta p_\perp}$$

exceeds the slit separation, the interference emerges robustly; when these are degraded, the fringes wash out even if flux is high.

Electron biprism interferometry, of which the MMP experiment is the canonical exemplar [30], has been extended extensively in electron optics. Later biprism studies varied the biprism voltage and lens settings to tune virtual source separation and overlap, revealing that fringe periodicity follows the Fresnel biprism relation

$$\ell = \frac{\lambda(a+b)}{d}$$

once the apparatus geometry and de Broglie wavelength are fixed. Drift in voltage, mechanical stability, or source temperature—any factor that broadens the velocity distribution or randomizes phase—reduces fringe visibility. Conversely, stabilizing the environment increases contrast. The dependence is on ensemble coherence and phase modulators, not on single–particle mystical behavior.

The Aharonov–Bohm effect [31] in electron interferometers provides a particularly clean demonstration of phase–only modulation in otherwise free electron paths. In ring or two–path geometries where electrons pass through field–free regions but enclose a magnetic flux, the shift in interference fringes is entirely due to a gauge–invariant phase acquired by the electron ensemble,

$$\Delta\phi = \frac{e}{\hbar}\Phi.$$

No forces along the paths are required; the apparatus imposes a phase difference that redistributes detection probabilities across space. Visibility is contingent on coherence and indistinguishability; decoherers such as thermal noise, inelastic scattering, or path–information probes suppress the signal.

Electron holography and off–axis interferometry [32] take the same principle further by mixing a reference electron wave with an object–modulated beam. The recorded hologram encodes phase differences introduced by the specimen and reconstructs them through interference during detection or computationally. The preconditions for high–quality holograms are unambiguous: monoenergetic sources, long coherence lengths, and phase–stable optics.

Matter–wave beam splitting in controlled fields—using electrostatic or magnetic prisms, Wien filters, or ponderomotive interactions—also supports the deterministic phase–modulation account. Experiments that implement electron analogs of Mach–Zehnder interferometers [45] split and recombine electron beams with field regions whose actions are calculable and reversible. Interference contrast depends predictably on path–length difference, energy spread, and environmental decoherence, and can be tuned in and out by adjusting field strengths and path geometry.

The Kapitza–Dirac effect [34], where electrons diffract from a standing light wave, reinforces that periodic external fields act as phase gratings for electron ensembles. The diffraction angles follow the Bragg–like[15] condition associated with momentum exchange quanta from the optical lattice; yet, the observed visibility still depends on the electron energy spread and coherence.

Atom and neutron interferometry [35, 77], while not electron–based, provide independent corroboration of the ensemble–coherence thesis. In neutron interferometers, monolithic perfect–crystal beam splitters create path–dependent phase shifts that generate high–contrast fringes when the neutron beam is energy–filtered and thermally stabilized. Atom interferometers split Bose–condensed or thermal ensembles with light–pulse beam splitters and generate fringes whose visibility hinges on temperature (velocity spread), phase noise, and path symmetry.

Single–photon interference [78], often invoked to argue for intrinsic duality, is also interpretable through coherence and indistinguishability. When sources are narrowband and detectors integrate over coherence times, single–photon events still map onto interference patterns determined by the apparatus's phase response. When path marking or spectral broadening is introduced, visibility collapses.

Finally, controlled studies that explicitly vary the energy spread of electron sources show systematic changes in fringe visibility and periodicity consistent with de Broglie relations and apparatus geometry. Narrowing the spread increases transverse coherence length and stabilizes phase, while broadening it reduces visibility. The emergence and disappearance of fringes with purely spectral manipulations is difficult to reconcile with a picture that assigns wave behavior intrinsically to each electron, but it fits naturally with a deterministic ensemble account. The relation

$$\Delta\lambda \approx \frac{\lambda}{2}\frac{\Delta E}{E}$$

shows how energy spread sets wavelength spread and thus phase jitter across the ensemble.

15.2. Contradicting or Challenging Experiments

While the deterministic, ensemble–based interpretation of interference is strongly supported by many experiments, there exist several landmark studies that are widely interpreted as contradicting or at least challenging such a framework. These experiments are often cited as evidence for intrinsic wave–particle duality, contextuality, or nonlocality in quantum mechanics. In this section we review the most significant of these, with mathematical detail.

15.3. Delayed–Choice Quantum Eraser (Kim et al., 2000)

15.3.1. Delayed-Choice Experiments

Wheeler's delayed-choice setups [73] are often cited as evidence against deterministic apparatus mechanisms. However, the apparatus configuration at the moment of detection still defines the phase relations. The "choice" simply determines which deterministic phase map is realized; the probabilistic detection outcomes follow accordingly. Kim et al. [44] implemented a delayed–choice quantum eraser using entangled photon pairs. One photon of each pair passed through a double–slit apparatus, while its entangled partner was directed to detectors that could either preserve or erase which–path information. Remarkably, interference fringes in the coincidence counts appeared or disappeared depending on whether the which–path information was erased, even when the choice was made after the signal photon had traversed the slits.

Mathematically, the joint state can be written as

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|s_1\rangle|i_1\rangle + |s_2\rangle|i_2\rangle\big),$$

where $|s_j\rangle$ are the signal photon paths and $|i_j\rangle$ the idler states. If the idler states remain orthogonal, $\langle i_1|i_2\rangle = 0$, then the reduced density matrix of the signal photon is incoherent and no interference is observed. If the idler states are projected into a superposition basis, $\frac{1}{\sqrt{2}}(|i_1\rangle \pm |i_2\rangle)$, then coherence is restored and interference fringes reappear. This dependence on measurement basis challenges a purely deterministic ensemble picture.

a. Our Reinterpretation of Delayed-Choice Quantum Eraser. In the experiment of Kim et al. [44], entangled photon pairs are used to demonstrate that interference can be "erased" or "restored" depending on the measurement basis of the idler photon. In the ensemble view, we argue this is not retrocausality but post-selection: the coincidence counting procedure partitions the ensemble into subensembles with preserved or destroyed coherence. The interference information is intrinsic to the entangled state and the apparatus, not to the geometric path of any individual photon.

15.4. Wheeler's Delayed–Choice Experiment

Wheeler proposed, and later experiments realized, a delayed–choice interferometer in which a photon enters a Mach–Zehnder interferometer and the decision to insert or remove the second beam splitter is made after the photon has passed the first splitter. If the second splitter is present, interference fringes are observed; if absent, the photon is detected as if it had traveled a definite path. The paradox is that the choice of measurement seems to retroactively determine whether the photon behaved as a wave or a particle.

The probability of detection at output port D_1 is

$$P(D_1) = \frac{1}{2}\big(1 + \cos\Delta\phi\big),$$

if the second beam splitter is present, where $\Delta\phi$ is the phase difference between the two arms. If the splitter is absent, the probabilities reduce to $P(D_1) = P(D_2) = 1/2$, independent of $\Delta\phi$. The apparent retroactive dependence is difficult to reconcile with a deterministic ensemble model only if we don't consider ensemble behaviour requires coherence to be maintained all the way to the detector. The phase shift causing the interference take place at the beam splitters which are placed relative chiral angle[4].

16. OPERATIONAL LOCUS OF INTERFERENCE IN THE MACH–ZEHNDER INTERFEROMETER

16.1. Setup and notation

We consider a standard Mach Zehnder interferometer (MZI) with two 2×2 beam splitters, BS_1 and BS_2, and two mirrors. Let the input state be a single-mode field incident on port a with vacuum at port b, written as the column vector $|\psi_{\rm in}\rangle = (1,\,0)^{\mathsf T}$ in the mode basis $\{a, b\}$. The two arms accumulate a relative phase $\Delta\phi$ between their optical paths. Detection occurs at output ports D_1 and D_2.

We model each lossless beam splitter by a unitary $U(\chi)$ that encodes both the 50:50 splitting and the device's *chiral orientation*[5] χ, i.e., whether reflection induces a relative phase advance or delay into a given output port due to coating sequence, substrate orientation, and geometric placement.

[4] "Chiral" here denotes the operational orientation that sets the sign conventions for reflection/transmission phases; it is not a parity-violating material property.

[5] "Chiral" as defined in the above footnote

16.2. Beam splitter unitaries and chiral orientation

A convenient 50:50 parameterization that separates the physical splitting ratio from a controllable orientation phase is

$$U(\chi) \;=\; \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i\,e^{i\chi} \\ i\,e^{-i\chi} & 1 \end{pmatrix}, \tag{46}$$

where χ encodes the device's effective reflection phase convention relative to its mechanical placement. Flipping or rotating the beam splitter changes $\chi \mapsto -\chi$, thereby swapping which output port receives constructive versus destructive interference when the arms are recombined. Different notational conventions in the literature are unitarily equivalent up to global phases and port relabeling.

16.3. Interferometer transformation and detection probabilities

Let the first beam splitter be $U(\chi_1)$, the arm phase accumulation be

$$P(\Delta\phi) \;=\; \begin{pmatrix} e^{+i\Delta\phi/2} & 0 \\ 0 & e^{-i\Delta\phi/2} \end{pmatrix}, \tag{47}$$

and the second beam splitter be $U(\chi_2)$. The total transformation from input to output is

$$T(\Delta\phi;\chi_1,\chi_2) \;=\; U(\chi_2)\,P(\Delta\phi)\,U(\chi_1). \tag{48}$$

Applying T to $|\Psi\rangle_{in}$ and taking intensities at the two output ports yields

$$P(D_1) \;=\; \cos^2\!\left(\frac{\Delta\phi + \chi_2 - \chi_1}{2}\right), \tag{49}$$

$$P(D_2) \;=\; \sin^2\!\left(\frac{\Delta\phi + \chi_2 - \chi_1}{2}\right). \tag{50}$$

Equations (49)–(50) make explicit that interference is *operationally enacted* at the second beam splitter: it is the relative geometry and orientation of BS_1 and BS_2 (i.e., $\chi_2 - \chi_1$) that sets the reference against which the arm phase $\Delta\phi$ is converted into output statistics.

Derivation of output intensities

a. Definitions. Let

$$U(\chi) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i\,e^{i\chi} \\ i\,e^{-i\chi} & 1 \end{pmatrix}$$

,

$$P(\Delta\phi) = \begin{pmatrix} e^{+i\Delta\phi/2} & 0 \\ 0 & e^{-i\Delta\phi/2} \end{pmatrix},$$

and take the input state as the column vector

$$|\Psi\rangle_{\rm in} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

The total transformation is

$$T(\Delta\phi; \chi_1, \chi_2) = U(\chi_2)\, P(\Delta\phi)\, U(\chi_1).$$

b. Apply $U(\chi_1)$*.*

$$U(\chi_1)\, |\Psi\rangle_{\rm in} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i\, e^{-i\chi_1} \end{pmatrix}.$$

c. Apply $P(\Delta\phi)$*.*

$$P(\Delta\phi)\, U(\chi_1)\, |\Psi\rangle_{\rm in} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{+i\Delta\phi/2} \\ i\, e^{-i\chi_1}\, e^{-i\Delta\phi/2} \end{pmatrix}.$$

d. Apply $U(\chi_2)$ *and read out amplitudes.* Output amplitudes at the two ports (mapped to detectors D_1, D_2) are

$$\psi_{D_1} = \frac{1}{\sqrt{2}} \left[e^{+i\Delta\phi/2} + i\, e^{i\chi_2}\, i\, e^{-i\chi_1}\, e^{-i\Delta\phi/2} \right]$$

$$= \frac{1}{\sqrt{2}} \left[e^{+i\Delta\phi/2} - e^{i(\chi_2-\chi_1)}\, e^{-i\Delta\phi/2} \right],$$

$$= \frac{i}{\sqrt{2}} \left[e^{-i\chi_2}\, e^{+i\Delta\phi/2} + e^{-i\Delta\phi/2} \right]$$

$$T(\Delta\phi; \chi_1, \chi_2) = U(\chi_2)\, P(\Delta\phi)\, U(\chi_1). \tag{51}$$

Up to an overall global phase (physically irrelevant), these simplify to sinusoidal dependence on $\Delta\phi + \chi_2 - \chi_1$. Taking intensities:

$$P(D_1) = |\psi_{D_1}|^2 = \cos^2\!\left(\frac{\Delta\phi + \chi_2 - \chi_1}{2} \right)$$

,

$$P(D_2) = |\psi_{D_2}|^2 = \sin^2\!\left(\frac{\Delta\phi + \chi_2 - \chi_1}{2} \right).$$

e. Remarks. Only the phase difference $\chi_2 - \chi_1$ matters; individual χ's and global phases can be absorbed by port relabeling or unobservable factors. Removing $U(\chi_2)$ prevents coherent mixing, yielding $P(D_1) = P(D_2) = 1/2$ independent of $\Delta\phi$.

16.4. Absence of the second beam splitter and loss of coherence

If BS_2 is removed, the arm fields are directed to D_1 and D_2 without coherent mixing. The detection events are then governed by single-arm intensities,

$$P(D_1) \;=\; P(D_2) \;=\; \frac{1}{2}, \tag{52}$$

independent of $\Delta\phi$. No retrocausal effect is needed: without the unitary mixing that converts relative phase into amplitude interference, phase remains locally unobserved in the detection statistics. In ensemble terms, removing BS_2 constitutes an operational decoherence with respect to the output measurement, not a dynamical erasure of the arm phases themselves.

16.5. Coherence to the detector: ensemble determinism

From a deterministic ensemble perspective, visibility arises only if coherence is *maintained up to the measurement that mixes the paths.* The arm phase $\Delta\phi$ is accumulated physically along the trajectories, but the conversion of that phase into constructive/destructive outcomes occurs at the recombination unitary. Thus, the ensemble behaves deterministically under the apparatus geometry: the presence and orientation of BS_2 determine whether the ensemble's relative phase is operationally tested (yielding Eqs. (49)–(50)) or not (yielding equal probabilities). The apparent "retroactive dependence" vanishes once one recognizes that the output statistics are functions of the *full* interferometer unitary, not of the arm phases in isolation.

16.6. Remarks on conventions and experimental practice

Different communities employ distinct beam-splitter phase conventions (for example, $U = \frac{1}{\sqrt{2}}\left(\begin{smallmatrix} 1 & i \\ i & 1 \end{smallmatrix}\right)$, or variants with $-i$ in the off-diagonal entries). These choices correspond to different assignments of the internal phases χ and to different port-labeling conventions, but they yield identical measurable predictions. In experimental settings, mirror coatings, substrate thickness, and the physical "handedness" of the optical layout determine the values of χ_1 and χ_2; their difference fixes which output port appears bright or dark for a given phase shift $\Delta\phi$. Maintaining high visibility requires careful alignment so that coherence is preserved up to BS_2, thereby avoiding unintended path-distinguishability.

16.6.1. Quantum Eraser

Quantum eraser experiments [7] show that interference visibility depends on whether which-path information is available. In our framework, the apparatus configuration (including entangling or erasing devices) deterministically sets the phase coherence conditions. The disappearance or reappearance of fringes reflects deterministic phase preparation, not retrocausality.

16.7. Single–Photon Interference with Long Temporal Separation

Experiments with single photons emitted at long intervals still show interference buildup over time [24]. The deterministic ensemble view would argue that coherence length and indistinguishability across the apparatus time window explain this. However, critics point out that if only one photon is present in the apparatus at a time, the ensemble is not physically simultaneous, suggesting that interference is an intrinsic property of each photon's wavefunction.

The visibility of interference fringes is given by

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

and remains high as long as the coherence length $L_c = c/\Delta\nu$ exceeds the path difference, even when photons are temporally separated.

a. Single-Photon Interference with Long Temporal Separation. Experiments such as those of Grangier et al. [24] show interference even when photons are emitted with long intervals between them. The orthodox interpretation is that each photon interferes with itself. In the deterministic ensemble framework, the explanation is that the apparatus defines deterministic path differences, and the ensemble coherence is preserved across the coherence time. Each photon samples one trajectory according to its initial transverse position, and the cumulative sum of all such trajectories produces the interference pattern. The time of arrival is determined by the apparatus-imposed path length differences, consistent with the MMP biprism experiment.

16.8. Bell Inequality Violations

Bell–type experiments [81] test correlations between entangled particles. The CHSH inequality,

$$S = |E(a, b) + E(a, b') + E(a', b) - E(a', b')| \leq 2,$$

is violated in quantum mechanics, with S reaching up to $2\sqrt{2}$. Experimental violations of this inequality rule out local deterministic hidden–variable theories. While not directly double–slit interference, these results are often invoked to argue against any fully deterministic reinterpretation of quantum phenomena.

16.9. Kochen–Specker Contextuality

The Kochen–Specker theorem shows that noncontextual hidden–variable models cannot reproduce quantum predictions. Experiments implementing contextuality tests [26] confirm that measurement outcomes depend on the measurement context, contradicting deterministic models that assign pre–existing values independent of context.

16.10. Weak Measurement Studies

16.10.1. Weak Measurement and Path Ambiguity

Weak measurement experiments [8] suggest particles take "ambiguous" paths. From our perspective, the apparatus imposes a deterministic phase structure across all possible paths; weak measurements probe ensemble averages of this structure. The apparent ambiguity arises from probabilistic detection, not from indeterminacy in the deterministic phase map. Kocsis et al. [27] performed weak measurements of photon momentum in a double–slit experiment, reconstructing average trajectories that resembled classical paths. The weak value formalism defines the average momentum as

$$p_w(x) = \frac{\langle \psi_f | \hat{p} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle},$$

where $|\psi_i\rangle$ and $|\psi_f\rangle$ are pre– and post–selected states. These results are interpreted by some as evidence that photons follow trajectories even in interference, but the dependence on weak values and post–selection complicates deterministic interpretations.

a. Weak Measurement Studies. Kocsis et al. [27] performed weak measurements of photon momentum in a double-slit setup, reconstructing average trajectories. The weak value of momentum is defined as

$$p_w(x) = \frac{\langle \psi_f | \hat{p} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle},$$

where $|\psi_i\rangle$ and $|\psi_f\rangle$ are pre- and post-selected states. These reconstructed trajectories are not evidence of individual particle paths, but ensemble averages shaped by apparatus-imposed phase relations. Thus, rather than refuting determinism, they support the view that the apparatus deterministically structures the ensemble statistics.

Supporting experiments (Davisson–Germer, biprism, Mach–Zehnder, atom interferometry) consistently show that apparatus-defined potentials and geometry deterministically impose phase gradients, producing interference. Experiments often interpreted as contradictory (delayed-choice, quantum eraser, weak measurement) can be reinterpreted: the apparatus still deterministically defines the phase structure, while probabilistic detection outcomes give the appearance of paradox. Thus, the universal mechanism remains intact: deterministic apparatus-imposed phase preparation underlies all interference phenomena.

16.11. Reframing Double-Slit Type Experiments as Supportive Evidence

The double-slit experiment has long been regarded as the quintessential paradox of quantum mechanics, suggesting that a single particle interferes with itself. However, when viewed through the deterministic ensemble framework developed in this manuscript, the apparent mystery dissolves. The apparatus imposes deterministic phase relationships on the ensemble, and the interference pattern emerges from the cumulative effect of these phase modulations across indistinguishable, monoenergetic particles.

Formally, let the initial transverse density matrix of the beam be $\rho(x, x')$, where x and x' denote transverse coordinates in the source plane. The apparatus (slits, biprism, or crystal) imposes a phase modulation $\phi(x)$ on each trajectory. The detection probability at a point y on the screen is then given by

$$P(y) = \int dx\, dx'\, \rho(x, x')\, e^{i[\phi(x)-\phi(x')]}\, K(y|x)K^*(y|x'),$$

where $K(y|x)$ is the propagator from source point x to detector point y. The interference fringes arise from the off-diagonal terms of $\rho(x, x')$, i.e. the coherence of the ensemble. Temporal separation between particles does not affect this, provided the coherence length

$$L_c \approx \frac{\hbar}{\Delta p_\perp}$$

exceeds the path difference. Thus, even when photons or electrons arrive one at a time, the deterministic apparatus-imposed phase relations ensure that the ensemble builds up the interference pattern.

The visibility of the fringes is quantified by

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

and depends directly on the degree of coherence preserved by the apparatus. Any disturbance that introduces which-path information reduces the off-diagonal terms of $\rho(x, x')$ and lowers V.

a. Synthesis. The so-called double slit or double path experiments, when analyzed through the group of monoenergetic indistinguishable ensemble framework, turn out to be supportive of our thesis. They all demonstrate that interference visibility depends on ensemble group velocity coherence, indistinguishability, and apparatus-imposed phase modulation, not just on intrinsic wave-particle duality of single particles. The probabilistic nature of detection is preserved. We only propose the mechanism of those probabilities are governed by the implicit laws of quantum mechanics and the apparatus geometry.

17. CLARIFYING OUR PROPOSED MECHANISM AND PROBABILISTIC OUTCOMES

It is important to clarify the precise meaning of "proposed mechanism" developed within the framework in this manuscript. The deterministic mechanism referred to here is not a claim that individual detection events are predetermined. Rather, it denotes the fact that the laws of quantum mechanics themselves — conservation of energy and momentum, phase accumulation, coherence conditions, and apparatus geometry — act as deterministic constraints that shape the structure of the probability distribution observed in interference experiments.

In this view, the Born rule remains valid: the probability of detecting a particle at position y is given by

$$P(y) = |\psi(y)|^2,$$

where $\psi(y)$ is the wavefunction amplitude at the detector. The individual outcome of a single detection event is probabilistic, but the form of $P(y)$ is deterministically governed by the apparatus and the underlying quantum laws. Thus, the interference fringes are reproducible and predictable, even though each particle arrives at a random location.

This distinction can be formalized using the density matrix formalism. Let the initial transverse density matrix of the beam be $\rho(x, x')$, and let the apparatus impose a phase modulation $\phi(x)$. The detection probability is then

$$P(y) = \int dx\, dx'\, \rho(x, x')\, e^{i[\phi(x)-\phi(x')]}\, K(y|x)K^*(y|x'),$$

where $K(y|x)$ is the propagator from source point x to detector point y. The deterministic mechanism lies in the apparatus-imposed phase relations $\phi(x)$ and the conservation laws encoded in $K^*(y|x')$, while the probabilistic outcome is the random sampling of $P(y)$ by individual particles.

The coherence length,

$$L_c \approx \frac{\hbar}{\Delta p_\perp},$$

sets the scale over which off-diagonal terms of $\rho(x,x')$ contribute to interference. When L_c exceeds the path difference, interference fringes appear; when it does not, the fringes vanish. This again illustrates the dual role: deterministic apparatus conditions define the probability landscape, while probabilistic detection fills it in.

In summary, the framework advanced here is best described as a *deterministic mechanism for probabilistic outcomes.* The deterministic mechanism is provided by the implicit laws of quantum mechanics themselves, which ensure that conservation rules and phase relations structure the ensemble statistics. The probabilistic outcomes are the individual detection events, which remain inherently random. This interpretation avoids the pitfalls of hidden-variable theories by not claiming preassigned outcomes, while still emphasizing the deterministic role of the apparatus and quantum laws in shaping the observed interference patterns.

17.1. Apparatus-driven phase shifts and realistic interference estimates

a. Deterministic mechanism for probabilistic outcomes. The apparatus (slits, biprism, electrostatic/magnetic lenses, or crystal fields) deterministically imposes path-length differentials and local phase shifts on the beam. Individual detections remain probabilistic, but the interference pattern—the structure of the probability distribution—is fixed by geometry, energy, and coherence. Two complementary routes capture this:

b. (i) Phase from path-length differential. For two coherent alternatives with path-length difference $\Delta L(x,y)$ at detector coordinates (x,y), the phase difference is

$$\Delta\phi(x,y) \;=\; \frac{2\pi}{\lambda}\,\Delta L(x,y),$$

with intensity

$$I(x,y) \;\propto\; 1+\cos\bigl(\Delta\phi(x,y)\bigr) \;=\; 2\cos^2\Bigl(\frac{\Delta\phi(x,y)}{2}\Bigr).$$

A modest, spatially varying ΔL across the beam cross-section yields fringes. For example, if $\Delta L = 10\lambda$ locally, then $\Delta\phi = 20\pi$ and the intensity returns to a bright fringe (periodicity). What matters is the gradient of $\Delta L(x,y)$ across (x,y), which maps to fringe spacing.

c. (ii) Phase from local electromagnetic potential (electron optics). Electrons traversing an electrostatic potential $V(\mathbf{r})$ acquire phase through the local wavenumber

$$k(\mathbf{r}) \;=\; \frac{1}{\hbar}\sqrt{2m\bigl(E-eV(\mathbf{r})\bigr)} \;\approx\; k_0\Bigl[1-\frac{eV(\mathbf{r})}{2E}\Bigr],$$

valid for $|eV| \ll E$, where E is the kinetic energy and $k_0 = \sqrt{2mE}/\hbar$. The accumulated phase along a path Γ is

$$\phi_\Gamma \;=\; \int_\Gamma k(\mathbf{r})\,ds \;\approx\; k_0 L_\Gamma \;-\; \frac{k_0}{2E}\,e\int_\Gamma V(\mathbf{r})\,ds,$$

so a phase difference between two alternatives Γ_1, Γ_2 is

$$\Delta\phi \;\approx\; k_0\,\Delta L \;-\; \frac{k_0}{2E}\,e\int_{\Gamma_1-\Gamma_2} V(\mathbf{r})\,ds.$$

Thus, both geometric path-length and local field-induced phase contribute deterministically to $\Delta\phi$.

d. Why atomic-scale gravity is negligible. Gravitational deflection at atomic scales is vanishingly small. Using a lensing-like estimate $\theta \sim 4GM/(rc^2)$ with $M \sim 10^{-26}$ kg and $r \sim 10^{-10}$ m gives $\theta \sim 10^{-52}$ radians, utterly negligible. By contrast, electromagnetic potentials of even millivolts across nanometer scales produce phase shifts orders of magnitude larger via the $k(E-eV)$ dependence above. Interference in electron and photon apparatus is therefore governed by electromagnetic and geometric effects, not spacetime curvature at the atomic scale.

e. Realistic numerical example (electrons). Consider $E = 50\,\text{keV}$ electrons with de Broglie wavelength $\lambda \approx 5.3\times10^{-12}$ m. A path-length differential of

$$\Delta L \;=\; 10\lambda \;\approx\; 5.3\times10^{-11}\,\text{m}$$

yields

$$\Delta\phi \;=\; \frac{2\pi}{\lambda}\Delta L \;=\; 2\pi\times10 \;=\; 20\pi\ \text{rad},$$

which corresponds to a bright fringe (periodicity). A spatially varying $\Delta L(x)$ with slope $\partial_x \Delta L$ sets the fringe spacing Δx by the condition $\Delta\phi(x+\Delta x)-\Delta\phi(x) = 2\pi$, i.e.

$$\Delta x \;=\; \frac{\lambda}{\partial_x \Delta L}.$$

Similarly, a weak, uniform electrostatic potential offset ΔV over an arm of length L adds

$$\Delta\phi_V \;\approx\; -\frac{k_0}{2E}\,e\,\Delta V\,L,$$

which can be tuned to shift or wash out fringes depending on coherence.

f. Time-of-arrival modulation (apparatus geometry). Path-length differences also modulate arrival times: $\Delta t \approx \Delta L/v$, where v is the particle speed. For $v \sim 2.6 \times 10^8$ m/s (50 keV electrons), the example above gives $\Delta t \sim 2 \times 10^{-19}$ s, too small to resolve directly but entirely sufficient to imprint phase. Interference visibility remains governed by the coherence length/time, not by simultaneous multi-particle occupancy.

g. Summary. Interference patterns arise when the apparatus deterministically sets ΔL and field-induced phase along alternative trajectories. Even path-length variations of a few to ten wavelengths produce robust fringes. The outcomes (individual hits) remain probabilistic, but the distribution's structure (fringes, shifts, visibility) is a deterministic consequence of apparatus geometry and electromagnetic fields, consistent with the broader thesis that quantum mechanics provides a deterministic mechanism for probabilistic outcomes.

18. PROPOSED MACROSCOPIC ENSEMBLE INTERFERENCE WITH CLASSICAL ENTITIES

Conventionally, it is said that the double-slit experiment applies only to quantum entities (electrons, photons, atoms) and not to classical macroscopic objects like cannon balls, primarily because the de Broglie wavelength of a single macroscopic object is extraordinarily small. Here, based on the ensemble-coherence principles discussed earlier, we propose an experiment to reveal interference-like effects for *macroscopic classical entities* by treating them not as isolated single bodies but as a *monoenergetic ensemble* of *identical*, *indistinguishable* entities that share a *group velocity* and thus can be characterized by a *group coherence length* and an *effective group wavelength* in the sense of their spatial phase ordering.
Key reframing:

- *Not single-particle interference:* We do not consider one macroscopic entity at a time (as in the classical cannon-ball analogy). Instead, we consider a coherent ensemble ("large balls") that propagates inertially with minimal transverse and longitudinal velocity spread, preserving phase ordering in the ensemble.

- *Smooth splitting into two sub-ensembles:* The ensemble passes through two *regions* (wide "slits" or channels) that divide the group into two sub-ensembles without destroying coherence. The splitting must be enacted by a *smooth gradient* across the flow (e.g., air flow field, wind nozzles, fluidized medium, conveyor fields) to avoid stochastic kicks that would introduce large $\Delta v_\perp$.

- *Controlled path difference:* A deterministic gradient in the splitting regions induces a controlled path difference between the sub-ensembles. Downstream, at a definite distance, the spatial overlap of these sub-ensembles produces an *interference-like* density modulation analogous to fringes, *provided* coherence is maintained and phase ordering survives.

18.1. Operational Definitions for a Macroscopic Ensemble

We define quantities by analogy to our quantum ensemble framework, but explicitly as *operational* (measurable) macroscopic parameters:

- *Group velocity:* v_{group} — mean velocity of the ensemble center-of-mass flow.

- *Velocity spreads:* $\Delta v_\parallel$ and $\Delta v_\perp$ — longitudinal and transverse velocity spreads. Coherence requires $\Delta v_\perp$ and $\Delta v_\parallel$ to be very small compared to v_{group}.

- *Phase ordering field:* An externally imposed, spatially smooth field (e.g., aerodynamic airflow, vibrational phase, conveyor phasing) that defines phase across the beam cross-section. This substitutes for quantum phase and ensures consistent timing/position correlation.

- *Effective group coherence length:* ℓ_c — the transverse distance over which phase ordering persists. Interference-like modulation requires $\ell_c \gtrsim w$, where w is the effective aperture/region width that splits the beam.

- *Effective group wavelength:* $\lambda_{\rm eff}$ — a spatial periodicity in the ensemble's phase ordering (e.g., induced by a periodic forcing or timing modulation) that plays the role of a "wavelength" in determining fringe spacing in the far field.

18.2. Decoherence Thresholds in Macroscopic Regime

The same structural conditions that suppress interference in quantum beams apply to classical ensembles via their operational analogs:

$$\Delta\phi \approx k_{\rm eff}\,\Delta\theta\, w = \frac{2\pi}{\lambda_{\rm eff}}\,\Delta\theta\, w \gtrsim 2\pi \quad \Rightarrow \quad \Delta\theta \gtrsim \frac{\lambda_{\rm eff}}{w}, \tag{53}$$

where $\Delta\theta$ is the angular divergence of the ensemble flow and $k_{\rm eff} \equiv 2\pi/\lambda_{\rm eff}$ is the effective wave number defined by the phase ordering mechanism (not quantum de Broglie).

Equivalently, in momentum/velocity terms for a particle of mass m:

$$\Delta\phi \approx \frac{\Delta p_\perp\, w}{\hbar_{\rm op}} \gtrsim 2\pi \quad \Rightarrow \quad \Delta v_\perp \gtrsim \frac{2\pi\,\hbar_{\rm op}}{m\,w}. \tag{54}$$

Here $\hbar_{\rm op}$ is a formal scale parameter capturing the strength of phase ordering and sensitivity of the measurement to transverse perturbations. It is *not* Planck's constant; rather, it encodes the operational phase rigidity of the macroscopic ensemble. Practically, coherence is lost when $\Delta v_\perp$ rises above a threshold set by the phase-ordering protocol.

Define transverse coherence length:

$$\ell_c \sim \frac{\lambda_{\rm eff}}{\Delta\theta}, \qquad \text{interference-like modulation requires } \ell_c \gtrsim w. \tag{55}$$

This maps one-to-one onto the conditions used in quantum interferometry, replacing quantum λ with $\lambda_{\rm eff}$.

18.3. Experimental Design Concept

a. Apparatus geometry:

- *Source:* A feeder line produces a stream of identical spheres (“large balls”) with narrow velocity distribution (e.g., controlled conveyor, air track, or low-friction chute) yielding v_{group} with $\Delta v_\parallel / v_{group} \ll 10^{-3}$ and $\Delta v_\perp / v_{group} \ll 10^{-6}$.

- *Splitter regions (“slits”):* Two adjacent, wide channels with *gradient fields* (e.g., laminar air flows shaped by nozzle arrays) that smoothly deflect the ensemble into two sub-ensembles without random kicks. The gradient sets a controlled path difference ΔL.

- *Phase ordering:* Imposed via synchronized mechanical vibration or periodic airflow modulation at frequency f, establishing $\lambda_{\rm eff} = v_{group}/f$ as the spatial periodicity of phase in the ensemble frame.

- *Detection plane:* A downstream array (high-speed camera, pressure/impact sensors) at distance L images the spatial density of impacts. Data are integrated over many runs to obtain ensemble density maps.

b. Target signature:

$$s \approx \frac{\lambda_{\rm eff}\, L}{d}, \qquad V \sim \exp\left[-\left(\frac{w}{\ell_c}\right)^2\right], \tag{56}$$

where d is the center-to-center spacing of the two splitter regions. We expect a density modulation (“fringe-like” bands) with spacing s, and visibility V controlled by coherence (phase-ordering fidelity, angular divergence, velocity spreads).

18.4. Practical Constraints and Tolerances

- *Angular divergence:* Require $\Delta\theta \lesssim \lambda_{\rm eff}/w$. With $w = 0.1$ m and $\lambda_{\rm eff} = 1$ mm, this implies $\Delta\theta \lesssim 10^{-2}$ rad (achievable with careful flow conditioning).

- *Velocity spreads:* For $m \sim 0.1$–1 kg balls and $v_{group} \sim 1$–5 m/s, target $\Delta v_\perp \lesssim 10^{-3}$–$10^{-2}$ m/s; $\Delta v_\parallel \lesssim 10^{-3}$–$10^{-2}$ m/s to prevent longitudinal dephasing.

- *Phase stability:* The imposed modulation f must be phase-locked across both channels to within $\sim 1^\circ$ equivalent, ensuring ℓ_c spans w and d.

- *Gentle splitting:* Use smoothly varying aerodynamic fields or soft guide vanes; avoid turbulent transitions (Reynolds conditioning), granular collisions, or stick–slip effects that inject random $\Delta v_\perp$.

18.5. Interpretation and Equivalence

This macroscopic experiment does not rely on quantum de Broglie wavelength of individual balls. Instead, it exploits:

1. **Ensemble coherence** (phase ordering of the group),
2. **Smooth splitting** into two sub-ensembles,
3. **Controlled path difference** yielding phase differences,
4. **Downstream overlap** producing density modulation analogous to interference fringes.

Under these conditions, the observed modulation is *operationally equivalent* to interference patterns in quantum beams, because the *same coherence criteria* apply: $\ell_c \gtrsim w$, $\Delta\theta \lesssim \lambda_{\rm eff}/w$, and visibility V set by transverse spread and phase-ordering fidelity. The crucial point is that interference is a *group phenomenon*; by constructing a macroscopic ensemble with engineered phase coherence, we can reproduce interference-like signatures without invoking single-particle quantum behavior.

18.6. Relation to Quantum Coherence and Decoherence

This proposal mirrors established quantum interferometry logic:

- *Coherence length and visibility:* The macroscopic $V(w) \sim \exp\left[-(w/\ell_c)^2\right]$ parallels electron and atom interferometer visibility laws [77].

- *Decoherence channels:* Random kicks, turbulence, timing jitter act as macroscopic analogs of environmental decoherence [79], increasing effective $\Delta v_\perp$ and diminishing ℓ_c.

- *Ensemble statistics:* As with single-electron double-slit build-up [70], a clear modulation emerges statistically after many impacts, not from a single trajectory.

18.7. Numerical Sketch

Let $v_{group} = 2.0$ m/s, modulation frequency $f = 2$ Hz $\Rightarrow \lambda_{\text{eff}} = v_{group}/f = 1$ m. Take splitter spacing $d = 0.5$ m and detection distance $L = 10$ m:

$$s = \frac{\lambda_{\text{eff}} L}{d} = \frac{1 \cdot 10}{0.5} = 20 \text{ m}. \tag{57}$$

To obtain a practical s (e.g., tens of cm to meters), increase f or reduce L/d. For $f = 20$ Hz ($\lambda_{\text{eff}} = 0.1$ m), $d = 0.5$ m, $L = 5$ m:

$$s = \frac{0.1 \cdot 5}{0.5} = 1 \text{ m}. \tag{58}$$

Impose $\Delta\theta \lesssim \lambda_{\text{eff}}/w$ with $w = 0.1$ m, $\lambda_{\text{eff}} = 0.1$ m $\Rightarrow \Delta\theta \lesssim 1$ rad (loose). For sharp fringes, tighten to $\Delta\theta \lesssim 10^{-2}$–$10^{-3}$ rad via flow straighteners and phase-locking; this increases ℓ_c and V.

- This is an *operational* analog of interference, not quantum de Broglie interference of single macroscopic objects. It tests the thesis that interference is fundamentally a *coherence-of-ensemble* phenomenon.
- Success hinges on engineering *phase ordering* and maintaining ultra-low velocity spreads. The experiment bridges statistical physics, fluid dynamics, and interferometry.
- A positive result would underscore that the "mystery" of double-slit is not about single particles, but about coherence, phase, and ensemble indistinguishability—concepts that transcend the quantum/classical divide when implemented operationally.

19. EXPERIMENTAL PROGRAM: ELECTRON GUN ARRAY WITH VELOCITY CONTROL AND ELECTROMAGNETIC SLIT ANALOGS

We propose a controllable, modular platform to probe interference as a function of (i) transverse and longitudinal velocity spreads and (ii) field-defined "slits" via electromagnetic (EM) structures. The apparatus decouples geometric aperture effects from kinematic and field-induced phase control, enabling precise tests of visibility V versus $\Delta v_\perp$, $\Delta v_\parallel$, and effective slit parameters (field strength, gradient, and extent). This directly interrogates the ensemble-coherence thesis and quantifies thresholds predicted by

$$V \approx V_0 \exp\left[-\left(\frac{\Delta v_\perp w}{\lambda}\right)^2\right], \qquad \Delta\theta \gtrsim \frac{\lambda}{w}, \qquad \ell_c \gtrsim w,$$

and the momentum–field relation

$$\Delta p_\perp \approx qBL.$$

19.1. Array of Electron Guns and Velocity Control

a. Architecture. An array (e.g., $N = 8$–32) of independently tunable electron guns produces quasi-parallel beams with adjustable kinetic energies and emittance. Each gun is paired with:

- Electrostatic lenses (Einzel lenses) for longitudinal velocity tuning ($v_\parallel$) and energy spread minimization (ΔE).
- Magnetic/electrostatic deflectors for transverse velocity control ($\Delta v_\perp$), implemented as weak, well-characterized steering fields.
- Adjustable collimators to set effective beam width w and angular divergence $\Delta\theta$.

b. Control parameters. For each beam i:

$$(v_\parallel)_i, \quad (\Delta v_\parallel)_i, \quad (\Delta v_\perp)_i, \quad w_i, \quad \Delta\theta_i.$$

The array allows:

1. *Transverse scans:* Fix E and w, vary $\Delta v_\perp$ in fine steps (e.g., 1–50 m/s equivalent) to map $V(\Delta v_\perp)$.
2. *Longitudinal scans:* Fix $\Delta v_\perp$ and w, vary E (and hence λ) to map $V(\lambda)$ and fringe spacing $s = \lambda L/d$.
3. *Mixed scans:* Joint variation of $(\Delta v_\perp, \Delta v_\parallel)$ to quantify longitudinal dephasing vs. transverse washout.

19.2. Electromagnetic Field "Slits"

Instead of mechanical apertures, define two spatially separated interaction regions ("slits") using EM fields:

a. Magnetic slit analogs (Lorentz deflection). Two narrow, uniform-B regions of length L_B and width w_B located at positions corresponding to slit centers, impart controlled transverse momentum:

$$\Delta p_\perp = qBL_B, \qquad \Delta\theta \approx \frac{\Delta p_\perp}{p} = \frac{qBL_B}{p}.$$

The pair acts as coherent beam splitters when B is set to yield small, equal deflections and minimal $\Delta v_\perp$ dispersion.

b. Electrostatic slit analogs (phase plates). Two thin electrostatic phase regions with potential $V(x)$ imprint differential phases:

$$\Delta\phi(x) = \frac{1}{\hbar}\int eV(x)\,\frac{dz}{v_\parallel},$$

allowing precise phase control without physical edges. Field homogeneity and edges are smoothed to avoid scattering.

c. Field scans. Vary B or V to tune:

(i) path separation $d(B)$,
(ii) phase difference $\Delta\phi(V)$,
(iii) effective aperture $w_{\text{eff}}(B,V)$.
Target collapse threshold for magnetic case:

$$qB_cL_B \gtrsim \frac{2\pi\hbar}{w},$$

which matches the decoherence criterion $\Delta\phi \gtrsim 2\pi$ in momentum form.

19.3. Interference Geometry and Detection

a. Downstream region. Place a detection plane at distance L from the slit analogs. For two-beam interference:

$$s = \frac{\lambda L}{d}, \qquad V \sim \exp\left[-\left(\frac{w}{\ell_c}\right)^2\right], \quad \ell_c \sim \frac{\lambda}{\Delta\theta}.$$

Use high-sensitivity CCD/MCP detectors; integrate single-event impacts to recover ensemble fringes.

b. Measurement protocol.

1. Calibrate $\lambda(E)$, $p(E)$, $\Delta\theta(\Delta v_\perp)$ via beam diagnostics.
2. Record V vs. $(\Delta v_\perp)$ at fixed (E,w,d,L).
3. Record V vs. (B) and (V) for EM slit analogs at fixed (E,w,d,L).
4. Extract ℓ_c from $V(w)$ fits and compare to $\ell_c \sim \lambda/\Delta\theta$.
5. Verify threshold $qBL_B \approx 2\pi\hbar/w$ where visibility collapses.

19.4. Expected Relations and Tests

a. Transverse velocity spread dependence.

$$V(\Delta v_\perp) \approx V_0 \exp\left[-\left(\frac{\Delta v_\perp w}{\lambda}\right)^2\right], \quad \text{predicts rapid visibility loss when } \Delta v_\perp \gtrsim \frac{\lambda}{w}.$$

b. Field-induced collapse.

$$qB_cL_B \gtrsim \frac{2\pi\hbar}{w} \quad \Rightarrow \quad B_c \gtrsim \frac{2\pi\hbar}{qwL_B}.$$

Provides a tunable, non-mechanical route to test the $\Delta p_\perp$ threshold.

c. Fringe spacing validation.

$$s = \frac{\lambda L}{d} \quad \text{across } E \text{ scans;}$$

$$V(d,w) \text{ benchmarks } w_{\text{eff}}(B,V) \text{ vs. geometry.}$$

19.5. Numerical Illustration (Representative Parameters)

Consider 50 keV electrons:

$$\lambda \approx 5.5\times10^{-12}\,\text{m}, \quad p \approx 1.2\times10^{-22}\,\text{kg m/s}.$$

Let $w = 10\,\mu\text{m}$, $d = 1\,\mu\text{m}$, $L = 1\,\text{m}$:

$$s = \frac{\lambda L}{d} \approx 5.5\,\text{mm}.$$

Transverse spread threshold:

$$\Delta v_\perp \gtrsim \frac{\lambda}{w}\cdot\frac{p}{m_e} \approx \frac{5.5\times10^{-12}}{1.0\times10^{-5}}\cdot\frac{1.2\times10^{-22}}{9.11\times10^{-31}} \approx 72\,\text{m/s},$$

consistent with the decoherence criterion $\Delta p_\perp \gtrsim 2\pi\hbar/w$.

Magnetic slit analog with $L_B = 0.1\,\text{m}$:

$$B_c \gtrsim \frac{2\pi\hbar}{qwL_B} \approx \frac{6.63\times10^{-34}}{(1.60\times10^{-19})(1.0\times10^{-5})(0.1)} \sim 4.1{\times}10^{-4}\,\text{T},$$

experimentally accessible. Scanning B through this scale should sharply reduce V.

19.6. Extensions and Precision Considerations

- *Array coherence:* Synchronize guns to common phase references (RF timing) to maintain ensemble indistinguishability and minimize inter-beam Δv mismatches.
- *Detector response:* Characterize timing windows, bandwidth, and spatial PSF; interpret V via distinguishability D to respect complementarity:

$$V \le \sqrt{1-D^2}, \qquad D \equiv D(\Delta v_\perp, \Delta v_\parallel, R_{\text{det}}).$$

- *Cross-frame analysis:* If components move (e.g., detector stage scans), transform state and response, compute observables in the detector's proper frame to avoid spurious frame effects.
- *EM field homogeneity:* Edge smoothing and gradient control to prevent uncontrolled $\Delta p_\perp$; map $w_{\text{eff}}(B,V)$ via field simulations and beam profiling.

This program isolates how transverse and longitudinal velocity spreads, as well as field-defined slit analogs, govern interference visibility. By replacing mechanical slits with tunable EM regions, we can quantitatively verify the momentum-based decoherence threshold and demonstrate that interference is a property of *ensemble coherence* rather than single-particle mysticism. The array architecture further permits statistical averaging and systematic scans to produce high-confidence maps of V across parameter space, directly supporting the ensemble-based, observer-relative reinterpretation.

20. MATERIAL DISPERSION AND EFFECTIVE OPTICAL PATH

Photons interacting with matter acquire phase shifts through the medium's dielectric response. The refractive index $n(\omega)$, determined by bound-charge polarization, modifies the optical path length:

$$\phi = k_0 n(\omega) L,$$

where $k_0 = 2\pi/\lambda_0$ is the vacuum wavenumber. Spatial variations $n(x, y, z)$ across the beam footprint impose transverse phase gradients $\partial_x \phi, \partial_y \phi$, steering the beam and producing interference modulation [10].

20.1. Interface-Induced Phase Shifts

At interfaces, reflection and transmission coefficients carry angle- and polarization-dependent phases. This produces lateral beam shifts such as the Goos–Hänchen effect (longitudinal) and the Imbert–Fedorov effect (transverse) [11–13]. Additionally, coupling to surface polaritons modifies the propagation constant, imprinting deterministic phase offsets [14].

20.2. Crystal Periodicity and Coherent Scattering

For photons, Bragg diffraction arises from the periodic modulation of $\epsilon(\mathbf{r})$, producing constructive interference at specific angles [15]. For electrons, the Davisson–Germer experiment demonstrated that the crystal lattice acts as a diffraction grating, with the periodic electrostatic potential modulating the electron phase [69]. Modern studies confirm that coherent scattering from periodic potentials deterministically structures the interference pattern [40].

20.3. Neutral-Particle Analogues

Neutral atoms and neutrons also acquire deterministic phase shifts via non-electromagnetic potentials. Casimir–Polder and van der Waals interactions near surfaces produce measurable phase differences in atom interferometry [18, 19]. Macroscopic gravity produces the Colella–Overhauser–Werner (COW) phase shift in neutron interferometers:

$$\Delta\phi_{\text{grav}} = \frac{mgA}{\hbar v},$$

where A is the interferometer area and v the neutron velocity [20].

20.4. Discussion: Electromagnetic Effects and Universality

When we say "electromagnetic effects cannot be at work," it is crucial to distinguish between *external applied fields* and the *intrinsic electromagnetic response of matter*. For photons and electrons, the dominant deterministic phase mechanisms at slit and crystal scales are electromagnetic in origin (dielectric response, lattice potentials), but they are intrinsic to the apparatus, not externally imposed. For neutral particles, deterministic phase arises from Casimir–Polder potentials and macroscopic gravity. Thus, the universal mechanism is: deterministic apparatus-defined potentials (electromagnetic, surface, or gravitational) shape the probability distribution, while detection remains probabilistic.

21. CRYSTAL PERIODICITY AND COHERENT SCATTERING

21.1. Davisson–Germer Experiment Revisited

The Davisson–Germer experiment (1927) [69] demonstrated that electrons scattered from a nickel crystal exhibit diffraction patterns analogous to X-ray Bragg scattering. In the conventional interpretation, the crystal lattice acts as a diffraction grating, imposing phase relations determined by the Bragg condition:

$$2d \sin\theta = n\lambda,$$

where d is the lattice spacing, θ the scattering angle, and λ the de Broglie wavelength.

21.2. Group Ensemble Phase Shifts from the Lattice

From a group of monoenergetic indistinguishable ensemble perspective, the periodic electrostatic potential of the lattice modifies the electron wavefunction phase along each trajectory:

$$\phi(\mathbf{r}) = \frac{1}{\hbar} \int_{\Gamma} \sqrt{2m\big(E - U_{\text{lattice}}(\mathbf{r})\big)}\, ds.$$

This integral encodes both longitudinal and transverse velocity components. The lattice potential U_{lattice} thus imprints structured phase differences across the beam, leading to the observed interference maxima.

21.3. Velocity Gradient Interpretation

The interference pattern implies that the incoming beam is not perfectly uniform but acquires deterministic velocity gradients:

- **Longitudinal gradient:** Variations in effective path length and group velocity along different crystal channels produce small differences in arrival phase.
- **Transverse gradient:** The periodic potential deflects trajectories slightly, introducing transverse momentum components that map into angular interference fringes.

Thus, the lattice enforces a structured velocity distribution across the beam cross-section. The observed diffraction peaks are the macroscopic manifestation of these deterministic gradients.

21.4. Role of Monoenergetic Indistinguishable Particles

Fringe visibility is maximized when the incoming electrons are monoenergetic and indistinguishable. Minimizing the spread in both longitudinal and transverse velocities ensures that the apparatus-imposed phase gradients dominate, rather than being washed out by beam incoherence. This condition was effectively realized in the Davisson–Germer setup, where a well-collimated, nearly monoenergetic electron beam was used.

21.5. Modern Reinterpretations

Contemporary studies of electron diffraction and interference [40] confirm that phase shifts imposed by crystal potentials can be understood as group velocity-gradient effects. The apparatus defines the phase map $\phi(x, y)$, while individual detection events remain probabilistic. This aligns with the broader thesis that quantum mechanics provides a group behavior mechanism for probabilistic outcomes.

22. SUPPORTING EXPERIMENTS

22.1. Davisson–Germer (1927)

The scattering of electrons from a nickel crystal demonstrated diffraction peaks consistent with Bragg's law [69]. In our framework, the periodic lattice potential deterministically imposes both longitudinal and transverse velocity gradients on the electron beam, producing structured phase differences that manifest as diffraction maxima. The requirement of a monoenergetic, indistinguishable beam ensured that apparatus-imposed phase dominated over incoherent spread.

22.2. Electron Biprism Interference

Tonomura's biprism experiments [70] showed stable electron interference fringes even with single-electron detection. The biprism's electrostatic potential deterministically modulates the phase across the beam cross-section, creating a transverse velocity gradient. The probabilistic detection events accumulate into a deterministic interference pattern.

22.3. Mach–Zehnder Interferometry

Both electron and neutron Mach–Zehnder interferometers [3] demonstrate controllable phase shifts by inserting potentials or varying path lengths. The apparatus deterministically sets $\Delta\phi$, while detection remains probabilistic. This directly supports the claim that interference is a deterministic mechanism for probabilistic outcomes.

22.4. Atom Interferometry

Atom interferometers reveal phase shifts due to Casimir–Polder potentials near surfaces [19] and gravitational potentials in the Colella–Overhauser–Werner (COW) experiment [20]. These show that neutral particles also acquire deterministic phase from apparatus-defined potentials, extending universality beyond charged particles.

23. ANCHOR EXPERIMENTS IN QUANTUM INTERFERENCE

To ensure theoretical consistency, we benchmark all calculations against experiments where phase shifts have been directly measured.

23.1. COW Neutron Interferometer

Colella, Overhauser, and Werner (1975) [20] tilted a silicon neutron interferometer so one path was higher in Earth's gravitational potential. The phase shift is

$$\Delta\phi_{\mathrm{grav}} = \frac{mgA}{\hbar v},$$

with A the interferometer area and v the neutron velocity. For thermal neutrons, $\Delta\phi \sim 10$ rad. This anchors gravitational phase estimates.

23.2. Neutron Sagnac Effect

Rotating the interferometer introduces a phase proportional to angular velocity, the matter-wave analogue of the optical Sagnac effect [52]. Measured shifts are of order radians, anchoring inertial phase contributions.

23.3. Spin–Rotation Coupling

Recent neutron interferometry [53] observed phase shifts from spin–rotation coupling. Though small (fractions of a radian), they confirm interferometric sensitivity to subtle couplings.

23.4. Atom Interferometry

Cold-atom Mach–Zehnder interferometers [48] measure gravitational phases of 10–1000 rad, and Casimir–Polder potentials near surfaces [19]. These anchor both macroscopic gravity and atom–surface potentials.

23.5. Electron Biprism Interference

Tonomura's biprism experiments [70] showed stable fringes even with single electrons. Millivolt potentials across nanometers yield phase shifts of 10–100 rad, anchoring electromagnetic phase scales.

23.6. Davisson–Germer

Electron diffraction from nickel crystals [69] demonstrated Bragg peaks. Effective path differences correspond to many radians of phase, anchoring lattice-induced phase shifts.

24. MODERN EXPERIMENTAL PARALLELS AND ANALOGUES

Beyond the canonical double-slit and interferometry experiments (Davisson–Germer, Tonomura, Arndt, Cronin, etc.), several modern experimental programs provide strong analogies to the ensemble-based, observer-relative framework proposed here. These experiments demonstrate that interference phenomena are not restricted to "mystical" single-particle behavior, but emerge whenever ensembles of indistinguishable entities maintain coherence under controlled splitting and recombination.

24.1. Electron Biprism Interferometry with Field Control

Electron biprism interferometers use electrostatic or magnetic fields as tunable beam splitters and phase shifters. These setups allow precise control of transverse momentum kicks ($\Delta p_\perp$) and directly test visibility V as a function of field strength and velocity spread [46].

24.2. Electron Vortex Beams and Structured Electron Optics

Modern transmission electron microscopes (TEMs) can generate vortex beams with orbital angular momentum. These beams are manipulated by electromagnetic phase plates and holographic masks, effectively replacing mechanical slits with field-defined apertures [47]. This is directly analogous to our proposal of using EM fields instead of physical slits.

24.3. Cold Atom and Bose–Einstein Condensate Interferometry

Cold atom interferometers routinely vary longitudinal and transverse velocities by adjusting laser cooling and trapping parameters. Light pulses (Bragg or Raman transitions) act as beam splitters, providing tunable "slits" defined by electromagnetic fields. These experiments demonstrate ensemble coherence and velocity control in a macroscopic quantum system [48].

24.4. Macroscopic Ensemble Analogues

Experiments with bouncing oil droplets on vibrating baths (Couder & Fort) show interference-like patterns due to ensemble coherence and pilot-wave analogies. While not quantum, these experiments support the idea that interference can emerge from coherent ensembles of classical entities [49].

24.5. SPDC Photon Arrays and Multi-Photon Entanglement

Spontaneous parametric down-conversion (SPDC) sources produce entangled photon pairs and higher-order states. Multi-photon entanglement experiments (Zeilinger group)[78] demonstrate how ensemble indistinguishability and controlled phase shifts govern visibility

25. NUMERICAL ANCHORING OF CANONICAL EXPERIMENTS IN A MONOENERGETIC, ENSEMBLE-DETERMINISTIC FRAMEWORK

25.1. Framework: equal velocity, coherence length, and aperture transfer

We assume monoenergetic ensembles with equal longitudinal velocity v and narrow relative spread $\delta v/v \ll 1$. The de Broglie wavelength is

$$\lambda = \frac{h}{p} = \frac{h}{mv} \quad \text{(nonrelativistic)}, \tag{59}$$

and the longitudinal coherence length is

$$\ell_c \simeq v\,\tau_c, \tag{60}$$

where τ_c is the temporal coherence set by source bandwidth and path-stability. Interference visibility V is limited by

$$\Delta L \lesssim \ell_c, \qquad V \simeq V_0\,\exp\left[-\left(\frac{\Delta L}{\ell_c}\right)^2\right], \tag{61}$$

and by transverse mismatch controlled by the aperture transfer function $A(\mathbf{r})$ and the incoming beam profile $B(\mathbf{r})$:

$$\mathcal{O} = \frac{\left|\int A(\mathbf{r})\,B(\mathbf{r})\,e^{i\phi(\mathbf{r})}\,d^2\mathbf{r}\right|}{\int A(\mathbf{r})\,|B(\mathbf{r})|\,d^2\mathbf{r}}, \qquad V \approx \mathcal{O}\,V_0. \tag{62}$$

For Gaussian beams with waist w_0 and slit (or grid) width a, the Fraunhofer envelope sets a characteristic angular scale $\theta_{\rm env} \sim \lambda/a$, while the incident cross section controls coupling efficiency $\eta \sim \mathrm{erf}(a/\sqrt{2}\,w_0)$ and the effective contrast.

25.2. Davisson–Germer: electron diffraction on Ni (monoenergetic electrons)

Electrons accelerated at $V \approx 54\,\mathrm{eV}$ have momentum $p = \sqrt{2m_e eV}$ and de Broglie wavelength

$$\lambda = \frac{h}{\sqrt{2m_e eV}} \approx 0.167\,\mathrm{nm} \quad (V = 54\,\mathrm{eV}). \tag{63}$$

For Ni(111) with $d \approx 0.091\,\mathrm{nm}$, Bragg's law $n\lambda = 2d\sin\theta$ predicts a strong maximum near $\theta \approx 65^\circ$ (first order). The measured monoenergetic distribution (narrow δV) is essential: a broader δV convolves λ and smears the angular peak, reducing V approximately as

$$V \simeq \exp\left[-\left(\frac{\pi d\,\delta\lambda}{\lambda^2}\right)^2\right], \qquad \frac{\delta\lambda}{\lambda} \simeq \frac{1}{2}\frac{\delta V}{V}. \tag{64}$$

Transverse beam diameter w_0 relative to the crystal mosaic aperture sets acceptance and the width of the rocking curve; matching w_0 to the crystal's effective coherence patch maximizes V.

25.3. Photon interferometry: Michelson/Mach–Zehnder (slit width and cross section)

For a monochromatic source at $\lambda = 589\,\mathrm{nm}$ (sodium D-line), path-difference stability requires $\Delta L \ll \ell_c$; with a typical linewidth $\Delta\nu \sim 1\,\mathrm{GHz}$, $\tau_c \sim 1/\Delta\nu \sim 1\,\mathrm{ns}$ and $\ell_c \sim 0.3\,\mathrm{m}$ [85]. A single-slit of width a produces a Fraunhofer envelope

$$I(\theta) \propto \mathrm{sinc}^2\left(\frac{\pi a\sin\theta}{\lambda}\right), \tag{65}$$

so narrowing a increases the envelope width $\sim \lambda/a$ and tightens angular tolerances at recombination. The incoming beam waist w_0 and splitter aperture set mode overlap; the on-axis visibility scales with the overlap integral, $V \approx \exp\left[-(k\,\sigma_\perp\,\Delta\theta)^2\right]$, where $k = 2\pi/\lambda$ and $\sigma_\perp$ is the transverse coherence length determined by source size and optics [86].

25.4. Neutron interferometry: perfect-crystal splitters (equal velocity, path stability)

Thermal neutrons at $\lambda \sim 0.20$–$0.30\,\mathrm{nm}$ (e.g., $v \sim 1.5$–$2.0\,\mathrm{km/s}$) traverse centimeter-scale path separations in Si interferometers [87]. A gravitational phase shift for arm height difference h over length L is

$$\Delta\phi_g \simeq \frac{m_n g h L}{\hbar v}, \tag{66}$$

yielding $\Delta\phi_g \sim 10^{-3}$–$10^{-2}\,\mathrm{rad}$ for representative $h \sim$ mm, $L \sim$ cm, $v \sim 2\,\mathrm{km/s}$. Monoenergetic velocity selection (narrow δv) is critical; a spread δv induces phase washout $\delta\phi \approx (\partial\phi/\partial v)\,\delta v$ with visibility $V \approx \exp\left[-(\delta\phi)^2\right]$ [88]. Crystal acceptance and beam cross section (mosaic and Darwin width) enforce transverse mode matching; under- or overfilling reduces V by reducing coherent Bragg channels.

25.5. Atom interferometry: Raman beam splitters (monoenergetic ensemble and beam size)

For Cs atoms with $v \sim 10\,\mathrm{m/s}$, $\lambda = h/(mv) \sim 0.1\,\mathrm{nm}$. Three-pulse Raman sequences yield phase

$$\Delta\phi \simeq \mathbf{k}_{\mathrm{eff}} \cdot \mathbf{g}\, T^2, \tag{67}$$

with $|\mathbf{k}_{\mathrm{eff}}| \approx 2k$ and T the pulse separation, producing large phases (e.g., $\sim 10^7\,\mathrm{rad}$) for $T \sim 0.1$–$0.3\,\mathrm{s}$ [89]. Monoenergetic preparation (narrow velocity class) ensures equal v across arms; finite δv degrades V via inhomogeneous Doppler phase. The transverse atomic beam cross section relative to Raman beam waists w sets Rabi angle uniformity; the contrast scales as

$$V \approx V_0\, \langle \sin\theta(\mathbf{r})\rangle_{\mathbf{r}} \quad \text{with} \quad \theta(\mathbf{r}) \propto \Omega(\mathbf{r})\,\tau,\ \Omega(\mathbf{r}) \propto e^{-2r^2/w^2}. \tag{68}$$

Aperture (slit or spatial filter) improves V at the cost of flux by narrowing the transverse mode distribution [90].

25.6. Large-molecule interferometry: Talbot–Lau grids (grid period and velocity selection)

For C_{60} with mass $m \approx 720\,\mathrm{amu}$ and $v \sim 100$–$200\,\mathrm{m/s}$, the de Broglie wavelength is $\lambda \sim 2$–$4\,\mathrm{pm}$. A Talbot–Lau setup with grating period $d_g \sim 100\,\mathrm{nm}$ produces a near-field self-imaging distance

$$L_T = \frac{d_g^2}{\lambda} \sim 2.5\,\mathrm{m} \quad (\lambda = 4\,\mathrm{pm},\ d_g = 100\,\mathrm{nm}), \tag{69}$$

so practical instruments use fractional Talbot distances and multi-grating geometries [103]. Monoenergetic velocity selection (e.g., $\delta v/v \lesssim 5\%$) is mandatory; the fringe period at the detector

$$\Lambda \simeq \frac{L\,\lambda}{d_g} \tag{70}$$

is velocity-dependent, and averaging over δv reduces V as $V \approx \exp\big[-(L\,\delta\lambda/d_g\Lambda)^2\big]$. Grid open fraction f and beam width w_0 determine coherent mode occupancy; optimal w_0 aligns with grating acceptance to maximize $\mathcal{O}$.

25.7. Two-photon beam splitter statistics: Hong–Ou–Mandel (temporal bandwidth and cross section)

With degenerate SPDC photons of coherence time $\tau_c \sim 100\,\mathrm{fs}$, the coincidence rate vs delay τ is

$$P_c(\tau) = \frac{1}{2}\left(1 - V\, e^{-(\tau/\tau_c)^2}\right), \tag{71}$$

yielding a dip depth V near unity for well-matched spectral and spatial modes [92]. Transverse mode mismatch (fiber coupling, beam waists at the splitter) reduces V as $V \approx \mathcal{O}$, with $\mathcal{O}$ the spatial overlap integral. Narrowband filtering increases τ_c (and thus tolerance to path jitter) at the cost of flux.

25.8. Operational role of slits/grids and beam cross section in all cases

Across electrons, photons, neutrons, atoms, and molecules:

- *Monoenergetic ensemble:* Equal v fixes λ and stabilizes phase accumulation; finite δv directly maps to $\delta\lambda$ and phase washout $V \approx \exp\big[-(\delta\phi)^2\big]$.
- *Slits/grids as transfer functions:* Apertures impose $A(\mathbf{r})$ that sets transverse coherence and defines the envelope (e.g., sinc^2 or Talbot response), converting path phase into measurable contrast.
- *Incoming beam cross section:* The spatial mode $B(\mathbf{r})$ (waist w_0, divergence) controls overlap and coupling efficiency; underfilling yields low flux but high V, overfilling increases flux but reduces V via multimode averaging.
- *Detector bandwidth/acceptance:* Finite angular/temporal acceptance selects modes; visibility reported is always conditional on this acceptance (implicit ensemble conditioning).

This unified, deterministic group behavior mechanism view makes the “interference or not” outcome a function of coherence maintenance, aperture geometry, and mode matching—never retroactive, always operational.

26. CONSTANTS AND FORMULAS

We use the following constants:

$$\begin{aligned} m_n &= 1.675 \times 10^{-27}\ \mathrm{kg}, \\ h &= 6.626 \times 10^{-34}\ \mathrm{J \cdot s}, \\ \hbar &= 1.055 \times 10^{-34}\ \mathrm{J \cdot s}, \\ g &= 9.81\ \mathrm{m/s^2}. \end{aligned}$$

Interferometer geometry:

$$h_{\mathrm{sep}} = 0.01\ \mathrm{m}, \qquad L = 0.10\ \mathrm{m}.$$

For a neutron of kinetic energy E:

$$v_\parallel = \sqrt{\tfrac{2E}{m_n}}, \tag{72}$$

$$\lambda = \frac{h}{m_n v_\parallel}, \tag{73}$$

$$\Delta\phi_g = \frac{m_n g h_{\mathrm{sep}} L}{\hbar v_\parallel}. \tag{74}$$

27. NUMERICAL CALCULATION RESULTS

TABLE III. Thermal neutron interferometry: neutron energy E, longitudinal velocity $v_\parallel$, de Broglie wavelength λ, and gravitational phase shift $\Delta\phi_g$ for path separation $h_{\rm sep} = 1.0$ cm and arm length $L = 10$ cm.

E (meV)	$v_\parallel$ (m/s)	λ (nm)	$\Delta\phi_g$ (rad)	Notes
10	1380	0.286	2.6×10^{-3}	Cold neutrons
25	2200	0.181	1.6×10^{-3}	Thermal neutrons
50	3110	0.128	1.1×10^{-3}	Hot neutrons
100	4390	0.090	7.7×10^{-4}	Very hot neutrons

28. INTERPRETATION IN THE ENSEMBLE FRAMEWORK

28.0.1. Monoenergetic Ensemble

The neutron beam is velocity-selected by monochromators. A narrow spread $\delta v/v$ ensures a sharply defined λ, so the phase accumulation is predictable. The longitudinal velocity $v_\parallel$ fixes the de Broglie wavelength and thus the interferometric scale.

28.1. Role of Crystal Slits

The silicon perfect-crystal interferometer acts as a beam splitter via Bragg diffraction. Its Darwin width defines the angular acceptance; transverse divergence beyond this reduces overlap and visibility. This is analogous to the role of slits or biprism fields in electron experiments.

28.2. Cross-Sectional Beam Profile

The incoming neutron beam cross section must match the interferometer's acceptance window. Overfilling reduces the coherent fraction, underfilling reduces flux. The transverse coherence length is

$$\ell_\perp \approx \frac{\lambda}{\Delta\theta},$$

with $\Delta\theta$ the source angular size.

28.3. Detector Role

Detectors count neutrons at each output port. The observed sinusoidal modulation in count rate versus phase shifter angle is the ensemble average conditioned on coherence. Visibility is reduced by energy spread and divergence.

28.4. Operational Conditions

Coherence is preserved if:

- Path difference $\Delta L \lesssim \ell_c = v_\parallel \tau_c$ (longitudinal coherence length).
- Path separation $h_{\rm sep} \lesssim \ell_\perp$ (transverse coherence length).
- Crystal stability ensures stationary phase $\Delta\phi_g$ across the ensemble.

Part III

29. MEASUREMENT, SUPERPOSITION, AND APPARATUS COUPLING

29.1. Relational Superposition in Measurement and Apparatus Coupling

In conventional quantum mechanics, a system evolves from an initial state

$$|\psi_{\rm in}\rangle$$

to a final state

$$|\psi_{\rm out}\rangle$$

via a unitary operator $U(t)$. Superposition is typically described either in terms of spatial wavefunctions (position basis) or temporal evolution (energy eigenstates). Measurement introduces epistemological tension: collapse versus unitary evolution, observer versus system.

a. Relational Resolution. I propose that this uneasy epistemology may be rectified under a relational framework. Any quantum relational interaction can be interpreted as:

- a superposition of "initial" states in *space*,
- a superposition of "final" states in *time*,
- together forming a superposition in *spacetime*.

b. Spacetime Superposition. Formally, the amplitude for a relational process is expressed as a sum over spacetime trajectories:

$$\mathcal{A} = \sum_\gamma e^{iS[\gamma]/\hbar},$$

where γ denotes a relational trajectory in spacetime and $S[\gamma]$ is the action functional. This path integral formulation makes explicit that superposition is not confined to spatial or temporal slices, but is inherently a spacetime phenomenon.

c. Measurement as Coupling. Measurement corresponds to a relational coupling between system and apparatus:

$$|\psi_{\text{system}}\rangle \otimes |\psi_{\text{apparatus}}\rangle \quad \longrightarrow \quad \sum_i c_i \, |\psi_i^{\text{system}}\rangle \otimes |\psi_i^{\text{apparatus}}\rangle.$$

Here, the apparatus does not collapse the system but participates in a joint spacetime superposition. The relational Hilbert space encodes both system and apparatus trajectories, ensuring consistency across observers.

d. Conclusion. Thus, superposition is best understood as a relational structure in spacetime:

$$(\text{Space superposition} \;\oplus\; \text{Time superposition});$$

$$\Rightarrow \quad \text{Spacetime superposition}.$$

This perspective unifies measurement, superposition, and apparatus coupling, resolving epistemological unease by embedding quantum mechanics in a relational spacetime framework.

29.2. The Orthodox View of Quantum Mechanics

The "uneasy nature" of the epistemological conclusions of quantum mechanics can be rectified if we note that any quantum interaction can be interpreted as a superposition of "initial states" in *space* and "final states" in *time*. Together forming a superposition in *spacetime*. The spatial superposition arises from the instantaneous density matrix of the initial state, while the temporal superposition corresponds to the sum total of detections in time—manifested as the spatial distribution on the detector screen at the final state of the interaction.

Any quantum entity may be considered either as an individual particle or as a *group* or *ensemble* of identical, indistinguishable, monoenergetic entities [93].

All possible states of a system—each state representing one particle among many—can be characterized by state vectors that evolve in two distinct ways:

1. *Continuously*, via the Schrödinger time-dependent equation, describing deterministic evolution of a single entity as a conserved, isolated system.

2. *Discontinuously*, via statistical probability laws governing a large ensemble of identical, indistinguishable monoenergetic entities.

Measurement collapses the wavefunction. The act of detection selects one particle from the superposition represented by the ensemble wavefunction. This collapse or reduction is central to the epistemological discomfort surrounding quantum mechanics [94].

Spacetime determination of a quantum entity occurs in two ways:

1. By sending a probe signal to interact with the entity and return to the detector.

2. By capturing the moving entity directly with a detector.

In either case, only one entity is detected at a time—one possible state among many initial states in spatial superposition—yielding a final state in temporal superposition.

Method (1) introduces the *measurement problem*:

> If a probe signal is used to measure a quantum entity, it alters the entity's state. This is the *decoherence effect*, proposed to explain wavefunction collapse [95].

However, if a particle collapses another particle's wavefunction, what collapses the probe particle's wavefunction? This leads to the *Von Neumann chain* [96]—a sequence of entangled measuring devices ending in a presumed conscious observer.

Niels Bohr argued that the wavefunction of an observed particle cannot be disentangled from the probe used to measure it [97]. When one photon measures another, they become entangled. The measuring particle inherits its part of the wavefunction, requiring another device to collapse it, and so on.

This recursive entanglement implies that quantum laws governing material systems require an external, nonlocal entity to terminate the chain—often interpreted as a conscious observer [**?**]. Thus, decoherence alone cannot resolve the measurement problem without invoking consciousness.

Wave-particle duality lies at the heart of this dilemma. As noted above, state vector evolution is either continuous or discontinuous. This paper postulates that duality arises from the choice of reference frame:

> *Wave behavior is observed when a large ensemble of identical, indistinguishable, monoenergetic quantum entities is viewed from a rest frame (zero relative velocity).*
>
> *Particle behavior is observed when the reference frame has non-zero relative velocity with respect to the ensemble.*

Particle behavior also emerges when the ensemble decoheres—i.e., disperses and loses group coherence—causing a single entity to break away.

We further postulate that ambient energy fluctuations, analogous to *Brownian motion*, induce unpredictable deviations in quantum worldlines. These fluctuations render deterministic tracking of spacetime evolution infeasible. Final states cannot be deterministically linked to initial states; only probabilistic correlations are possible [**?**].

Measurements thus become statistical attributions, correlating initial ensemble states to final detector outcomes.

The classical *Eulerian viewpoint* enables continuous tracking only when the observer is co-moving with the system. This relative rest allows continuous measurement of the state vector.

30. SPACE-TIME MIXTURES AND MEASUREMENT SEQUENCES

From the linear independence of the states $A^{\rho v}$, it follows that:

$$u_p a_v = \delta_{vp} x_p^{\mu k}$$

which cannot be satisfied if more than one a_v is finite. Therefore, it is incompatible with the equations of motion of quantum mechanics to assume that the post-measurement state of the object-plus-apparatus is a mixture of states, each with a definite pointer position, unless we adopt the distinction proposed here: that such mixtures are mixtures in **space-time**, with each pointer position corresponding to a **point event in space-time**.

In other words, measurements that leave the system in a definite pointer state can be reconciled with the linear laws of quantum mechanics, only if the total state (the initial state and the final state), is treated as one space-time superposition. The initial object states considered as a superposition in space, and the final apparatus states as a superposition in time—and each determined by different observers.

Successive measurements yield final results directly related to the initial states of each run, with the **temporal order** of measurements entering into the outcomes.

30.1. Projection Operators and Measurement Chains

Let P_{jk} be the projection operator associated with the characteristic value q^j of the Heisenberg operator Q_j^H. Then the probability for the sequence $(q_a^1, q_\beta^2, \ldots, q_\mu^n)$ of n measurement results is:

$$P_{n\mu} \cdots P_{2\beta} P_{1a} \Phi, \quad \text{with normalized state vector } P_{n\mu} \cdots P_{2\beta} P_{1a} \Phi$$

If, after normalization, this expression is independent of the original state vector Φ, then the measurements have sufficed to determine the system completely—a **complete mixture** has been produced. Our knowledge of the system is then complete.

If the expression still depends on Φ, and Φ was not known initially, then the system is in an **incomplete mixture**. Further measurements or information are required for a complete description.

Thus, the state vector is a shorthand for the relevant information about the system's past that enables prediction of its future behavior. The density matrix plays a similar role, though it does not predict future behavior as completely as the state vector.

30.2. Probabilistic Correlations and Ambient Fluctuations

Probabilistic correlations become fundamental in quantum mechanics due to uncontrollable ambient fluctuations. These make it impossible to deterministically attribute a final state to a specific initial state.

The uneasy implications of quantum mechanics can be resolved if—and only if—we correlate correct final states with causally related initial states along the same worldlines. This requires maintaining a consistent reference frame from initial to final state and distinguishing:

- Superposition of states in **space**
- Superposition of states in **time**

30.3. Density Matrix and Temporal Evolution

To summarize:

- The density matrix represents the spatial distribution of one quantum entity or an ensemble at a given moment—an initial state.
- Ambient variations over infinitesimal time intervals yield new spatial distributions—new initial states.
- A series of these spatial distributions corresponds to a series of final states separated by infinitesimal time intervals.

Each spatial initial state corresponds to a final state in time. The sum total of these correlations constitutes a complete measurement of the entity in time.

However, due to ambient fluctuations, these correlations can only be established probabilistically.

30.4. Outlook: Re-examining Quantum Interpretations

Next, we will re-examine several foundational interpretations of quantum mechanics under this framework. Our goal is to demonstrate how the inherent weirdness of each interpretation can be remedied, and how their conclusions may be modified when viewed through the lens of space-time mixtures and ensemble-based realism.

For completeness, a brief account of each interpretation will be provided.

Let us consider sharp states $\sigma^1, \sigma^2, \ldots, \sigma^v$. If the initial state of the apparatus is denoted by a, then the initial state of the total system (apparatus plus object) is characterized by:

$$a \times \sigma^v$$

The interaction leads to the final state:

$$a \times \sigma^v \Rightarrow a^v \times \sigma^v$$

The state of the object remains unchanged—it still contains all the sharp states with which it started. However, the state of the apparatus changes and depends on the original state of the object. That is, one among all possible states of existence has been selected. The different states a^v correspond to pointer positions of the apparatus, each indicating a specific σ^v.

If the initial state of the object is not sharp but an arbitrary linear combination:

$$a_1\sigma^1 + a_2\sigma^2 + \ldots + a_v\sigma^v$$

then the state vector of the object-plus-apparatus after measurement becomes:

$$a \times \left\{\sum a_v\sigma^v\right\} \Rightarrow \sum a_v \left\{a^v \times \sigma^v\right\}$$

This follows from the linearity of the quantum mechanical equation of motion—the superposition principle.

30.5. Pointer Concordance and Statistical Correlation

In any measurement of the system (object plus apparatus), the two quantities—the measured observable of the object and the pointer position of the apparatus—always yield concordant results. Thus, one measurement is deemed unnecessary: the state of the object is inferred from the pointer position. This forms the foundation of the statistical correlation between the initial state of the object and the final state of the apparatus.

These statistical correlations are central to quantum mechanics and underpin its epistemological challenges.

30.6. Mixture vs. Superposition

Attempts to modify the orthodox theory often assume that the measurement result is not a superposition (as in Eq. 2), but a mixture of states:

$$a^\mu \times \sigma^\mu$$

This state emerges from the interaction with probability $|a_\mu|^2$, selecting one possibility from the ensemble.

However, it is generally accepted that the state represented by Eq. (2) has experimentally verified properties that mixtures like Eq. (3) do not. These distinctions are nearly impossible to detect in single cases, such as the Stern–Gerlach experiment. Thus, modifications to the orthodox theory are inconsistent with quantum principles, and the uneasy epistemological conclusions remain.

30.7. Relational Reference Frame Consistency

We assert that the key is maintaining a relationally consistent relative reference frame or observer viewpoint throughout the experiment—from initial to final state. This emphasizes that the observer's frame of reference determines whether the ensemble appears as a coherent wave or as discrete particle detections. A co-moving frame with the quantum entity preserves spatial coherence, while a stationary detector frame samples temporal events. This distinction is crucial for interpreting measurement outcomes without paradox.

Any given initial state of an electron in a beam corresponds to one spatial location in the cross-sectional distribution. This maps to one final state on the detector screen at a specific time. At another instant, a different initial spatial distribution yields a different final temporal distribution.

The sum of all initial spatial distributions must equal the sum of all final temporal distributions. The experiment is complete only when all spatial permutations of the identical particles are correlated with their corresponding detection times.

If initial points are not mixed with causally unrelated final points, the uneasy behavior of quantum states disappears, and Eq. (2) remains valid without paradox.

30.8. Space-Time Superpositions and Orthogonality

The notion of a superposition in space-time is a conceptual extension of the standard density matrix formalism. While conventional quantum mechanics treats spatial and temporal distributions separately, we propose that the ensemble of initial spatial states and the ensemble of final temporal detections together form a unified distribution over space-time. This does not violate quantum mechanics but reframes the interpretation of ensemble evolution.

Even though different values of v correspond to different pointer settings from different runs, they can be considered collectively as a superpositions in space-time. The total state of the object-apparatus is a superposition in space-time, not to be confused with:

- Superposition of initial object states (spatial density matrix) - Superposition of final object states (temporal density matrix via detector)

Assume the initial apparatus state is a superposition:

$$A^1, A^2, \ldots, A^\rho, \quad \text{with probabilities } P_\rho$$

Then the equation of motion yields:

$$A^\rho \times \sigma^v \to A^{\rho v} \times \sigma^v$$

Each $A^{\rho v}$ indicates the same object state σ^v via pointer position. Values of v exist as superpositions in time; values of σ^v exist as superpositions in space. Together, they form a space-time mixture.

Orthogonality follows:

$$A^{\rho v}, A^{\sigma v} = \delta_{\rho\sigma}\delta_{v\mu}$$

since $A^{\rho v} \times \sigma^v$ and $A^{\sigma v} \times \sigma^v$ arise from unitary transformations of orthogonal states. Orthogonality here refers to the distinguishability of pointer states in the Hilbert space of the apparatus. That is, $\langle A^{\rho v} | A^{\sigma v} \rangle = 0$ for $\rho \neq \sigma$, assuming idealized measurement channels. Operationally, this implies that different pointer positions correspond to mutually exclusive detector outcomes.

30.9. Generalized Superpositions and Measurement Postulates

If the initial object state is:

$$\sum a_v \sigma^v$$

then the post-measurement state of the system is:

$$A^P \times \sum a_v \sigma^v \to \sum a_v \left\{ A^{\rho v} \times \sigma^v \right\} = \Phi^\rho$$

with probabilities P_ρ.

According to the measurement postulate, this superposition should be equivalent to:

$$\Psi^{\mu k} = \sum_\rho x_\rho^{\mu k} \left\{ A^{\rho\mu} \times \sigma^\mu \right\}$$

These are the most general states with definite measured values λ_μ, coupled to pointer positions μ. If $P_{\mu k}$ is the probability of $\Psi^{\mu k}$, then:

$$\sum_k P_{\mu k} = |a_\mu|^2$$

The coefficients $x_\rho^{\mu k}$ depend on the initial amplitudes a_v.

However, Φ^ρ cannot simultaneously be a superposition of $\Psi^{\mu k}$ unless only one a_v is nonzero. A necessary condition is:

$$\Psi^{\mu k} = \sum_\rho u_\rho \Phi^\rho = \sum_{pv} u_\rho a_v \left\{ A^{\rho v} \times \sigma^v \right\}$$

31. SPACE-TIME SUPERPOSITIONS AND MEASUREMENT SEQUENCES

From the linear independence of the states $A^{\rho v}$, it follows that:

$$u_p a_v = \delta_{vp} x_p^{\mu k}$$

which cannot be satisfied if more than one a_v is finite. Therefore, it is incompatible with the equations of motion of quantum mechanics to assume that the post-measurement state of the object-plus-apparatus is a superposition of states, each with a definite pointer position, unless we adopt the distinction proposed here: that such superpositions are superpositions in **space-time**, with each pointer position corresponding to a **point event in space-time**.

In other words, measurements that leave the system in a definite pointer state can be reconciled with the linear laws of quantum mechanics only if the total state is treated as a space-time mixture. The object's initial state is a superposition in space, and the object's final state or the apparatus state is a superposition in time—the initial and final states are as viewed by different observers.

Successive measurements yield final results directly related to the initial states of each run, with the **temporal order** of measurements entering into the outcomes.

31.1. Projection Operators and Measurement Chains

Let P_{jk} be the projection operator associated with the characteristic value q^j of the Heisenberg operator Q_j^H. Then the probability for the sequence $(q_a^1, q_\beta^2, \ldots, q_\mu^n)$ of n measurement results is:

$$P_{n\mu} \cdots P_{2\beta} P_{1a} \Phi, \quad \text{with normalized state vector } P_{n\mu} \cdots P_{2\beta} P_{1a} \Phi$$

If, after normalization, this expression is independent of the original state vector Φ, then the measurements have sufficed to determine the system completely—a **complete superposition** has been produced. Our knowledge of the system is then complete.

If the expression still depends on Φ, and Φ was not known initially, then the system is in an **incomplete**

superposition. Further measurements or information are required for a complete description.

Thus, the state vector is a shorthand for the relevant information about the system's past that enables prediction of its future behavior. The density matrix plays a similar role, though it does not predict future behavior as completely as the state vector.

31.2. Probabilistic Correlations and Ambient Fluctuations

Probabilistic correlations become fundamental in quantum mechanics due to uncontrollable ambient fluctuations. These make it impossible to deterministically attribute a final state to a specific initial state.

The uneasy implications of quantum mechanics can be resolved if—and only if—we correlate correct final states with causally related initial states along the same worldlines. This requires maintaining a consistent reference frame from initial to final state and distinguishing:

- Superposition of states in **space**
- Superposition of states in **time**

This emphasizes that the observer's frame of reference determines whether the ensemble appears as a coherent wave or as discrete particle detections. A co-moving frame with the quantum entity preserves spatial coherence, while a stationary detector frame samples temporal events. This distinction is crucial for interpreting measurement outcomes without paradox.

31.3. Density Matrix and Temporal Evolution

To summarize:

- The density matrix represents the spatial distribution of one quantum entity or an ensemble at a given moment—an initial state.
- Ambient variations over infinitesimal time intervals yield new spatial distributions—new initial states.
- A series of these spatial distributions corresponds to a series of final states separated by infinitesimal time intervals.

Each spatial initial state corresponds to a final state in time. The sum total of these correlations constitutes a complete measurement of the entity in time.

However, due to ambient fluctuations, these correlations can only be established probabilistically.

31.4. Outlook: Re-examining Quantum Interpretations

Next, we will re-examine several foundational interpretations of quantum mechanics under this relational framework. Our goal is to demonstrate how the inherent weirdness of each interpretation can be remedied, and how their conclusions may be modified when viewed through the lens of relational space-time superpositions and ensemble-based realism.

For completeness, a brief account of each interpretation will be provided.

32. REINTERPRETING QUANTUM INTERPRETATIONS IN LIGHT OF SPACE-TIME ENSEMBLE FRAMEWORK

32.1. Consistent Histories

In the two-slit experiment, the path by which a particle travels from the source to the detector—producing a flash of light—must be consistent with quantum physics. The consistent histories interpretation is mathematically equivalent to the probabilistic Copenhagen interpretation, but conceptually distinct. It avoids invoking a wavefunction that spreads omnidirectionally and collapses at a single spatial point upon detection.

Within the proposed framework, a large ensemble of indistinguishable, monoenergetic quantum entities—characterized by a group velocity, wavelength, and frequency—exhibits **wave-like behavior** when observed from a co-moving reference frame. This ensemble passes through the double slit, undergoing a collective phase shift due to interactions with the curved space-time near the slit atoms, and subsequently impacts the detector screen at definite locations.

The variation in their trajectories through the apparatus introduces a path difference, giving rise to the familiar interference pattern. Any influence that disrupts the ensemble's group coherence—such as decoherence or environmental perturbation—destroys the interference pattern.

This interpretation is fully consistent with quantum mechanics and aligns with the experimental results of Davisson and Germer, as well as single-electron interference experiments [**?**]. It provides a coherent explanation of the double-slit experiment without invoking counterintuitive notions such as a single particle splitting or interfering with itself. Instead, interference arises from the coherent evolution of an ensemble in space-time.

32.2. Decoherence Interpretation

Decoherence describes the process by which quantum superpositions become effectively classical due to entanglement with the environment, leading to the emergence of a single outcome at the macroscopic level [95]. This is conceptually aligned with our proposal that measurements by the apparatus are fundamentally **measurements in time**.

Each measurement selects one among many possible states of existence of the quantum entity. These possible states are in spatial superposition at the initial moment, as viewed from the rest frame of the entity. Each initial state corresponds to a detector reading—a final state world event. The collection of these final events, as seen from the rest frame of the apparatus (has non-zero relative velocity with the entity), forms a superposition in time.

Each detector reading corresponds to a possible realization of the entity's existence, as encoded in the initial state density matrix. Together, the initial and final states form a superposition in **space-time**.

Probabilities arise not from intrinsic indeterminacy, but from our incomplete knowledge of:

- Ambient fluctuations influencing the worldlines connecting initial and final states
- Variations in the spatial distribution of the initial state density matrix
- The inability to track individual worldlines of ensemble constituents

The uneasy conclusions of quantum mechanics emerge when unrelated world events—associated with different worldlines—are incorrectly correlated. Our framework resolves this by preserving causal consistency and reference frame alignment.

32.3. Ensemble Interpretation

The ensemble interpretation posits that each quantum entity (e.g., electron or photon) possesses definite properties (position, momentum), and the wavefunction encodes the statistical distribution of outcomes across many identically prepared systems [93].

However, this view assumes the reverse of our proposal. It treats the **apparatus** as an ensemble of possible outcomes, each corresponding to a particular detector reading, and assumes that the wavefunction of the apparatus mirrors that of the quantum entity.

In contrast, we assert:

- The quantum entity itself is an ensemble of indistinguishable, monoenergetic constituents
- The wavefunction represents the spatial superposition of this ensemble at a given moment
- The apparatus measurements occur at definite times and cannot exist in spatial superposition
- Apparatus readings form a superposition in **time**, not space

Only the combined wavefunction of the entity-apparatus system—spanning initial and final states—can be meaningfully described as a superposition in **space-time**. This reframing preserves the deterministic evolution of the ensemble while accounting for the statistical nature of measurement outcomes.

32.4. Hidden Variable Interpretation

The hidden variable interpretation assumes that quantum mechanics is incomplete, and that an underlying layer of reality contains additional information—hidden variables—that determine measurement outcomes.

This idea originates from the Einstein–Podolsky–Rosen (EPR) paradox, which argued that the quantum wavefunction does not provide a complete description of reality. Using entangled particles, EPR showed that one could predict both position and momentum of a particle with certainty, based on measurements performed on its entangled partner—without disturbing it. This suggested that quantum mechanics must be incomplete.

Two main schools of thought emerged:

- If no faster-than-light communication exists, hidden variables must exist
- The Copenhagen interpretation asserts that hidden variables are not determined until measurement

Under our framework, both views can be reconciled:

- There is no faster-than-light signaling
- The hidden variables are the implicit quantum mechanical laws encoded in the choice of eigenfunctions and eigenvalues

We further assert that the density matrix—representing the initial spatial distribution of the entity—is itself a form of hidden variable. The superposition of all possible states of existence in space (initial state) corresponds to all final states of identical, indistinguishable, monoenergetic entities, which coexist in time as the sum total of all detector points.

Only together—initial spatial superposition and final temporal superposition—can they be considered a superposition in **space-time**.

33. PHILOSOPHICAL SYNTHESIS AND FINAL INTERPRETATIONAL REMARKS

Our claim that both von Neumann and Bohm were correct in different senses is philosophically defensible. Von Neumann's proof assumes linear operators and Hilbert space structure; Bohm's theory introduces nonlocal hidden variables but retains quantum predictions. This is precisely why John von Neumann was not wrong, and David Bohm was also correct—even though he could not explicitly demonstrate where his framework diverged from von Neumann's proof.

The inherent non-locality of quantum theory arises from two foundational assumptions:

1. The congruent nature of Hilbert or configuration space in quantum theory

2. The time-dependent nature of the apparatus measurement wavefunction, or the assumption that the superposition principle of the apparatus in space-time is identical to that of the quantum entity

33.1. Aspect Experiment

The Aspect experiment is widely regarded as definitive evidence for quantum non-locality. It originates from John Bell's seminal paper, which proposed a mathematical inequality to test whether hidden variable theories could reproduce the predictions of quantum mechanics.

Bell's inequality was derived under the assumption that quantum eigenfunctions σ could be replaced by arbitrary functions λ intended to restore locality and encode additional information. However, this substitution undermined the quantum mechanical correlations, which depend critically on the linearity, orthogonality, and completeness of eigenfunctions.This substitution neglects the structural properties of quantum eigenfunctions—such as orthogonality, completeness, and linearity—which are essential for preserving quantum correlations. The function λ lacks these properties, and thus any theory built on such replacements cannot reproduce the predictions of quantum mechanics. Bell's theorem assumes locality and realism, but the mathematical structure of quantum mechanics (especially orthogonality and completeness of eigenstates) is not preserved in hidden variable models represented by any function λ that violate these assumptions.

Any theory that replaces σ with λ—as Bell did—permits non-orthogonal angles and breaks the structure of quantum correlations. Thus, the discrepancy between Bell's inequality and quantum predictions does not refute hidden variables per se, but rather invalidates theories that substitute quantum eigenfunctions with arbitrary functions.

In other words, Bell's inequality does not prove or disprove the existence of hidden variables. It only demonstrates that replacing σ with λ is inconsistent with quantum mechanics.

Therefore, the EPR paradox and its implications remain an open question. In a forthcoming paper, we will revisit EPR under the proposed framework and offer a logically consistent explanation that preserves quantum predictions while avoiding paradoxical conclusions.

33.2. Many Worlds Interpretation

The Many Worlds interpretation posits that the universe splits into multiple branches whenever a quantum event presents multiple possible outcomes. This can be reframed under our proposed framework.

Instead of saying "whenever the world is faced with a choice," we assert:

> "Whenever the object is a mixture (superposition) of states in space, all measurements are possible (singled out in time) choices (sum total of which is a mixtures (superposition)) in time."

These choices are realized as detector readings—flashes, clicks, or spots—each corresponding to a moment in time. In the double-slit experiment, the electron's path through slit A or slit B is not a self-interfering trajectory, but an initial spatial choice followed (along their world line trajectory) by different indistinguishable monoenergetic electrons to their final temporal choice at the detector. The resulting interference pattern emerges from the ensemble's coherent evolution as a mixture or superposition in space-time.

33.3. Quantum Logic Interpretation

Quantum logic attempts to redefine the logical structure of reality, suggesting that classical logic cannot be applied to quantum phenomena. However, it fails to specify where the boundaries lie—whether the correspondence principle is included or excluded from "everyday logic."

This leads to the illogical assumption of a world without logic, undermining the coherence of both classical and quantum reasoning. Our framework restores logical consistency by distinguishing between spatial and temporal superpositions and preserving causal structure across reference frames.

34. TECHNOLOGICAL IMPLICATIONS OF THE SPACE-TIME ENSEMBLE FRAMEWORK

The reinterpretation of quantum mechanics presented here is not only of philosophical and foundational significance, but also has potential technological consequences. By reframing measurement as a correlation of ensembles in space-time, several current challenges in quantum technologies may be addressed or advanced.

34.1. Quantum Computing and Error Correction

Quantum computers are limited by decoherence and noise, requiring resource-intensive error correction. In the present framework, decoherence can be understood as a misalignment of worldlines within the ensemble, rather than a fundamental collapse. This suggests new error-correction strategies that track ensemble correlations across time, potentially reducing overhead and improving scalability. Recent work emphasizes the centrality of decoherence in limiting quantum computation and the need for robust error correction [98–100].

34.2. Quantum Communication and Cryptography

Long-distance entanglement distribution is fragile, and Bell-test-based protocols are interpreted as requiring non-local correlations. By interpreting correlations as space-time ensemble consistency, rather than non-locality, new architectures for quantum repeaters and entanglement swapping may be developed. This could enhance the robustness of quantum key distribution against noise and loss. Entanglement swapping protocols have been extended to high-dimensional systems and shown to be central to quantum networks [101, 102].

34.3. High-Precision Interferometry

Large-scale interferometers with neutrons, atoms, or molecules are limited by decoherence and environmental fluctuations. The distinction between spatial superpositions (initial ensembles) and temporal superpositions (detector events) provides a design principle for maximizing coherence length and visibility. This has direct applications in gravitational wave detection, inertial navigation, and precision tests of fundamental physics. Matter-wave interferometry with composite quantum objects such as C_{60} molecules has already demonstrated the feasibility of macroscopic interference [103–105].

34.4. Macroscopic Quantum Systems

Extending interference to larger, more classical systems (e.g., optomechanical resonators, biomolecules) is experimentally challenging. The concept of space-time mixtures allows macroscopic interference to be interpreted without invoking paradoxical self-interference of single particles. This may inspire new experimental designs for probing the quantum-to-classical transition and for developing quantum-enhanced sensors [106, 107].

34.5. Quantum Simulation

Simulating many-body quantum systems is computationally difficult due to exponential Hilbert space growth. By treating ensembles as deterministic distributions in space-time, rather than mystical superpositions, new density-based or trajectory-based simulation methods may be developed. These could scale more efficiently, especially for open systems. Quantum trajectory theory and ensemble-based simulation methods have already proven powerful for modeling open quantum dynamics [108–110].

34.6. Relativistic Quantum Information and Quantum Gravity

Reconciling quantum mechanics with relativity often encounters paradoxes of simultaneity, collapse, and non-locality. By explicitly tying measurement to reference frames and worldlines, the present framework provides a natural bridge between relativistic causality and quantum correlations. This may advance both relativistic quantum communication protocols and phenomenological approaches to quantum gravity. Recent work on quantum reference frames highlights their importance for both foundations and applications [111–113].

34.7. Summary

The proposed framework replaces the notion of "mystical collapse" with causal, ensemble-based correlations in space-time. By distinguishing between spatial and temporal superpositions, and emphasizing the role of reference frames, it offers a coherent reinterpretation that may advance:

- Quantum error correction and scalable quantum computing
- Robust quantum communication and cryptography
- High-precision interferometry and sensing
- Macroscopic quantum experiments
- Efficient quantum simulation
- Relativistic quantum information and quantum gravity research

Thus, the ensemble-based, space-time interpretation not only resolves epistemological difficulties but also provides practical insights for the next generation of quantum technologies.

35. CONCLUSION

I have presented a relational reinterpretation of wave–particle duality grounded in observer-relative velocity. By distinguishing between incoming beam group velocity and transverse velocity spread, and embedding the framework in relativistic quantum mechanics, I offer a testable, universal model that connects foundational experiments [69, 75, 77] with modern theory. This approach reframes duality not as a paradox, but as an emergent property of relational quantum systems. I show the double-slit experiment does not reveal mystical self-interference of single particles. It reveals group behavior of monoenergetic indistinguishable entities from two different relative view points of two different relative frames.

This study has revisited three canonical experiments—Davisson–Germer electron diffraction, the Merli–Missiroli–Pozzi biprism interferometer, and the Rauch–Werner neutron interferometer. Re-examination demonstrates that the so–called wave–particle duality is not an intrinsic paradox of single quanta. The duality is a relational and emergent property of coherent ensembles of monoenergetic, indistinguishable particles. By reconstructing the conditions under which interference patterns appear, I have shown what the decisive factors are. These factors are the longitudinal velocity (fixing the de Broglie wavelength), the transverse velocity spread (fixing the coherence length), and the operational role of apertures, grids, or fields in defining the overlap of trajectories.

The Davisson–Germer data illustrate that sharp diffraction maxima arise only when the electron beam is sufficiently monoenergetic and collimated. The MMP biprism experiment shows that fringe spacing and visibility are determined by the interplay of λ, biprism geometry, and transverse coherence. Extending the same framework to neutrons, we quantified how energy, velocity, and gravitational phase shifts govern the observed visibility in perfect–crystal interferometers. In each case, the observed interference is not a mysterious duality of individual particles, but a relational outcome of ensemble propagation through well–defined apparatus functions.

The tables show that neutron energy determines velocity, wavelength, and gravitational phase shift. These quantities directly control the visibility of interference fringes. The relational ensemble framework emphasizes that once E, h_{sep}, L, and beam divergence are fixed, the trajectories and phases are operationally determined from source to detector.

Taken together, these results provide compelling evidence for a unified, operationally grounded relational framework in which interference phenomena across electrons, photons, neutrons, and atoms can be understood without invoking intrinsic mysterious wave–particle duality. Once the ensemble parameters (E, $v_{\parallel}$, $\Delta v_{\perp}$, coherence lengths) and apparatus geometry are fixed, the trajectories and phases are determined from source to detector. This perspective may not only demystify long–standing paradoxes, it may also offer a consistent foundation for interpreting both historical and modern interference experiments.

36. REFERENCES

[1] C. J. Davisson and L. H. Germer, “The scattering of electrons by a single crystal of nickel,” *Phys. Rev.*, vol. 30, no. 6, pp. 705–740, 1927.

[2] A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa, “Demonstration of single-electron buildup of an interference pattern,” *Am. J. Phys.*, vol. 57, no. 2, pp. 117–120, 1989.

[3] A. Zeilinger, R. Gähler, C. G. Shull, W. Treimer, and W. Mampe, “Single- and double-slit diffraction of neutrons,” *Rev. Mod. Phys.*, vol. 60, no. 4, pp. 1067–1073, 1988.

[4] F. Shimizu, “Specular reflection of very slow metastable neon atoms from a solid surface,” *Phys. Rev. Lett.*, vol. 86, no. 6, pp. 987–990, 2001.

[5] R. Colella, A. W. Overhauser, and S. A. Werner, “Observation of gravitationally induced quantum interference,” *Phys. Rev. Lett.*, vol. 34, no. 23, pp. 1472–1474, 1975.

[6] J. A. Wheeler, “The ‘past’ and the ‘delayed-choice’ double-slit experiment,” in *Mathematical Foundations of Quantum Theory*, A. R. Marlow (ed.), Academic Press, 1978.

[7] M. O. Scully, B.-G. Englert, and H. Walther, “Quantum optical tests of complementarity,” *Nature*, vol. 351, pp. 111–116, 1991.

[8] Y. Aharonov, D. Z. Albert, and L. Vaidman, “How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100,” *Phys. Rev. Lett.*, vol. 60, no. 14, pp. 1351–1354, 1988.

[9] R. Bach, D. Pope, S.-H. Liou, and H. Batelaan, “Controlled double-slit electron interference,” *New J. Phys.*, vol. 15, 033018, 2013.

[10] M. Born and E. Wolf, *Principles of Optics*, 7th ed., Cambridge University Press, 1999.

[11] F. Goos and H. Hänchen, “Ein neuer und fundamentaler Versuch zur Totalreflexion,” *Annalen der Physik*, vol. 436, no. 7–8, pp. 333–346, 1947.

[12] C. Imbert, “Calculation and experimental proof of the transverse shift induced by total internal reflection of a circularly polarized light beam,” *Phys. Rev. D*, vol. 5, no. 4, pp. 787–796, 1972.

[13] F. I. Fedorov, “K teorii polnogo vnutrennego

otrazheniya," *Doklady Akademii Nauk SSSR*, vol. 105, pp. 465–468, 1955.

[14] H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*, Springer, 1988.

[15] W. H. Bragg and W. L. Bragg, "The reflection of X-rays by crystals," *Proc. R. Soc. Lond. A*, vol. 88, no. 605, pp. 428–438, 1913.

[16] C. J. Davisson and L. H. Germer, "The scattering of electrons by a single crystal of nickel," *Phys. Rev.*, vol. 30, no. 6, pp. 705–740, 1927.

[17] R. Bach, D. Pope, S.-H. Liou, and H. Batelaan, "Controlled double-slit electron interference," *New J. Phys.*, vol. 15, 033018, 2013.

[18] H. B. G. Casimir and D. Polder, "The influence of retardation on the London–van der Waals forces," *Phys. Rev.*, vol. 73, no. 4, pp. 360–372, 1948.

[19] F. Shimizu, "Specular reflection of very slow metastable neon atoms from a solid surface," *Phys. Rev. Lett.*, vol. 86, no. 6, pp. 987–990, 2001.

[20] R. Colella, A. W. Overhauser, and S. A. Werner, "Observation of gravitationally induced quantum interference," *Phys. Rev. Lett.*, vol. 34, no. 23, pp. 1472–1474, 1975.

[21] Y.-H. Kim, R. Yu, S. P. Kulik, Y. Shih, and M. O. Scully, "A Delayed Choice Quantum Eraser," *Physical Review Letters*, vol. 84, no. 1, pp. 1–5, 2000.

[22] P. Grangier, G. Roger, and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences," *Europhysics Letters*, vol. 1, no. 4, pp. 173–179, 1986.

[23] S. Kocsis, B. Braverman, S. Ravets, M. J. Stevens, R. P. Mirin, L. K. Shalm, and A. M. Steinberg, "Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer," *Science*, vol. 332, no. 6034, pp. 1170–1173, 2011.

[24] P. Grangier, G. Roger, and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences," *Europhysics Letters*, vol. 1, no. 4, pp. 173–179, 1986.

[25] A. Aspect, J. Dalibard, and G. Roger, "Experimental test of Bell's inequalities using time-varying analyzers," *Physical Review Letters*, vol. 49, no. 25, pp. 1804–1807, 1982.

[26] A. Cabello, S. Filipp, H. Rauch, and Y. Hasegawa, "Proposed experiment for testing quantum contextuality with neutrons," *Physical Review Letters*, vol. 100, 130404, 2008.

[27] S. Kocsis, B. Braverman, S. Ravets, M. J. Stevens, R. P. Mirin, L. K. Shalm, and A. M. Steinberg, "Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer," *Science*, vol. 332, no. 6034, pp. 1170–1173, 2011.

[28] A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa, "Demonstration of single–electron buildup of an interference pattern," *American Journal of Physics*, vol. 57, no. 2, pp. 117–120, 1989.

[29] R. Bach, D. Pope, S.-H. Liou, and H. Batelaan, "Controlled double–slit electron interference," *New Journal of Physics*, vol. 15, 033018, 2013.

[30] G. Merli, G. F. Missiroli, and G. Pozzi, "On the statistical aspect of electron interference phenomena," *American Journal of Physics*, vol. 44, no. 3, pp. 306–307, 1976.

[31] Y. Aharonov and D. Bohm, "Significance of electromagnetic potentials in the quantum theory," *Physical Review*, vol. 115, no. 3, pp. 485–491, 1959.

[32] H. Lichte, "Electron holography: fundamentals, techniques and applications," *Reports on Progress in Physics*, vol. 59, no. 3, pp. 257–300, 1991.

[33] M. Schmid and P. Hommelhoff, "Electron interference and beam splitting in electric and magnetic fields," *Journal of Physics B: Atomic, Molecular and Optical Physics*, vol. 53, 045003, 2020.

[34] P. L. Kapitza and P. A. M. Dirac, "The reflection of electrons from standing light waves," *Proceedings of the Cambridge Philosophical Society*, vol. 29, pp. 297–300, 1933.

[35] H. Rauch, W. Treimer, and U. Bonse, "Experimental realization of coherent spinor beam splitting of neutrons," *Physics Letters A*, vol. 47, no. 5, pp. 369–371, 1974.

[36] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, "Optics and interferometry with atoms and molecules," *Reviews of Modern Physics*, vol. 81, no. 3, pp. 1051–1129, 2009.

[37] A. Zeilinger, "Experiment and the foundations of quantum physics," *Reviews of Modern Physics*, vol. 71, no. S2, pp. S288–S297, 1999.

[38] C. J. Davisson and L. H. Germer, "The Scattering of Electrons by a Single Crystal of Nickel," *Physical Review*, vol. 30, no. 6, pp. 705–740, 1927.

[39] G. Merli, G. F. Missiroli, and G. Pozzi, "On the Statistical Aspect of Electron Interference Phenomena," *American Journal of Physics*, vol. 44, no. 3, pp. 306–307, 1976.

[40] R. Bach, D. Pope, S. Liou, and H. Batelaan, "Controlled double-slit electron interference," *New Journal of Physics*, vol. 15, no. 3, 033018, 2013.

[41] W. Duane, "The Transfer in Quanta of Radiation Momentum to Matter," *Proceedings of the National Academy of Sciences*, vol. 9, no. 5, pp. 158–164, 1923.

[42] A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa, "Demonstration of single-electron buildup of an interference pattern," *American Journal of Physics*, vol. 57, no. 2, pp. 117–120, 1989.

[43] H. Arrabal, "Coulomb Field Modulation and Deterministic Interference in Quantum Systems," *PREreview*, 2025. [Preprint]

[44] Y.-H. Kim, R. Yu, S. P. Kulik, Y. Shih, and M. O. Scully, "A Delayed Choice Quantum Eraser," *Physical Review Letters*, vol. 84, no. 1, pp. 1–5, 2000.

[45] M. Schmid and P. Hommelhoff, "Electron Interference and Beam Splitting in Electric and Magnetic Fields," *Journal of Physics B: Atomic, Molecular and Optical Physics*, vol. 53, no. 4, 045003, 2020.

[46] W. Hasselbach, "Progress in electron- and ion-interferometry," *Rep. Prog. Phys.* **73**, 016101 (2010).

[47] J. Verbeeck, H. Tian, and P. Schattschneider, "Production and application of electron vortex beams," *Nature* **467**, 301–304 (2010).

[48] M. Kasevich and S. Chu, "Atomic interferometry using stimulated Raman transitions," *Phys. Rev. Lett.* **67**, 181–184 (1991).

[49] Y. Couder and E. Fort, "Single-particle diffraction and interference at a macroscopic scale," *Phys. Rev. Lett.* **97**, 154101 (2006).

[50] D. Bouwmeester, J.-W. Pan, M. Daniell, H. Weinfurter, and A. Zeilinger, "Observation of three-photon Greenberger–Horne–Zeilinger entanglement,"

Phys. Rev. Lett. **82**, 1345–1349 (1999).

[51] C. J. Villas-Boas, C. E. Máximo, P. J. Paulino, R. P. Bachelard, and G. Rempe, "Bright and dark states of light: The quantum origin of classical interference," *arXiv:2112.05512* (2021).

[52] S. A. Werner, J.-L. Staudenmann, and R. Colella, "Effect of Earth's rotation on the quantum mechanical phase of the neutron," *Phys. Rev. Lett.* **42**, 1103–1106 (1979).

[53] H. Lemmel, A. Danner, B. Demirel, R. Wagner, S. Sponar, and Y. Hasegawa, "Spin–rotation coupling observed in neutron interferometry," *npj Quantum Information* **6**, 1–6 (2020).

[54] B.-G. Englert, "Fringe visibility and which-way information: An inequality," *Phys. Rev. Lett.* **77**, 2154 (1996).

[55] A. Aspect, J. Dalibard, and G. Roger, "Experimental test of Bell's inequalities using time-varying analyzers," *Phys. Rev. Lett.* **49**, 1804 (1982).

[56] B. Hensen et al., "Loophole-free Bell inequality violation using electron spins separated by 1.3 km," *Nature* **526**, 682–686 (2015).

[57] Y. Liu et al., "Experimental test of wave–particle duality relations in asymmetric interferometers," *Nat. Quantum Inf.* **8**, 1–7 (2022).

[58] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*, Addison-Wesley (1995).

[59] C. J. Davisson and L. H. Germer, "The scattering of electrons by a single crystal of nickel," *Phys. Rev.* **30**, 705 (1927).

[60] N. Bohr, "The quantum postulate and the recent development of atomic theory," *Nature* **121**, 580–590 (1928).

[61] C. Rovelli, "Relational quantum mechanics," *Int. J. Theor. Phys.* **35**, 1637–1678 (1996).

[62] P. A. M. Dirac, "The quantum theory of the electron," *Proc. R. Soc. Lond. A* **117**, 610–624 (1928).

[63] W. H. Zurek, "Decoherence, einselection, and the quantum origins of the classical," *Rev. Mod. Phys.* **75**, 715 (2003).

[64] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, "Optics and interferometry with atoms and molecules," *Rev. Mod. Phys.* **81**, 1051 (2009).

[65] W. H. Zurek, "Decoherence, einselection, and the quantum origins of the classical," *Rev. Mod. Phys.* **75**, 715 (2003).

[66] A. Tonomura et al., "Demonstration of single-electron buildup of an interference pattern," *Am. J. Phys.* **57**, 117 (1989).

[67] N. Bohr, "The quantum postulate and the recent development of atomic theory," *Nature* **121**, 580–590 (1928).

[68] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Vol. 3 (Addison-Wesley, 1965).

[69] C. J. Davisson and L. H. Germer, "The scattering of electrons by a single crystal of nickel," *Phys. Rev.* **30**, 705 (1927).

[70] A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa, "Demonstration of single-electron buildup of an interference pattern," *Am. J. Phys.* **57**, 117 (1989).

[71] M. O. Scully and K. Drühl, "Quantum eraser: A proposed photon correlation experiment concerning observation and 'delayed choice' in quantum mechanics," *Phys. Rev. A* **25**, 2208 (1982).

[72] S. P. Walborn, M. O. Terra Cunha, S. Pádua, and C. H. Monken, "Double-slit quantum eraser," *Phys. Rev. A* **65**, 033818 (2002).

[73] J. A. Wheeler, "The 'past' and the 'delayed-choice' double-slit experiment," in *Mathematical Foundations of Quantum Theory*, ed. A. R. Marlow (Academic Press, 1978).

[74] V. Jacques, E. Wu, F. Grosshans, F. Treussart, P. Grangier, A. Aspect, and J.-F. Roch, "Experimental realization of Wheeler's delayed-choice GedankenExperiment," *Science* **315**, 966–968 (2007).

[75] M. Arndt, O. Nairz, J. Vos-Andreae, C. Keller, G. van der Zouw, and A. Zeilinger, "Wave–particle duality of C_{60} molecules," *Nature* **401**, 680–682 (1999).

[76] J. S. Bell, "On the Einstein Podolsky Rosen paradox," *Physics* **1**, 195–200 (1964).

[77] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, "Optics and interferometry with atoms and molecules," *Rev. Mod. Phys.* **81**, 1051–1129 (2009).

[78] D. Bouwmeester, J.-W. Pan, M. Daniell, H. Weinfurter, and A. Zeilinger, "Observation of three-photon Greenberger–Horne–Zeilinger entanglement," *Phys. Rev. Lett.* **82**, 1345–1349 (1999).

[79] W. H. Zurek, "Decoherence, einselection, and the quantum origins of the classical," *Rev. Mod. Phys.* **75**, 715–775 (2003).

[80] B.-G. Englert, "Fringe visibility and which-way information: An inequality," *Phys. Rev. Lett.* **77**, 2154–2157 (1996).

[81] A. Aspect, J. Dalibard, and G. Roger, "Experimental test of Bell's inequalities using time-varying analyzers," *Phys. Rev. Lett.* **49**, 1804–1807 (1982).

[82] B. Hensen et al., "Loophole-free Bell inequality violation using electron spins separated by 1.3 km," *Nature* **526**, 682–686 (2015).

[83] Y. Liu, X.-M. Hu, J.-S. Tang, Y.-F. Huang, C.-F. Li, and G.-C. Guo, "Experimental test of wave–particle duality relations in asymmetric interferometers," *Nat. Quantum Inf.* **8**, 1–7 (2022).

[84] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*, (Addison-Wesley, 1995).

[85] L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics*, Cambridge University Press, 1995.

[86] D. S. S. Chrysosthemos et al., "Quantum coherence versus interferometric visibility in a biased Mach–Zehnder interferometer," *Quantum Inf. Process.*, vol. 22, 2023.

[87] H. Rauch and S. A. Werner, *Neutron Interferometry: Lessons in Experimental Quantum Mechanics*, Oxford University Press, 2000.

[88] H. Rauch, "Neutron Interferometry: A Review," *Physica B*, vol. 551, pp. 1–8, 2015.

[89] M. Kasevich and S. Chu, "Atomic interferometry using stimulated Raman transitions," *Phys. Rev. Lett.*, vol. 67, no. 2, pp. 181–184, 1991.

[90] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, "Optics and interferometry with atoms and molecules," *Rev. Mod. Phys.*, vol. 81, pp. 1051–1129, 2009.

[91] M. Arndt et al., "Wave–particle duality of C_{60} molecules," *Nature*, vol. 401, pp. 680–682, 1999.

[92] C. K. Hong, Z. Y. Ou, and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference," *Phys. Rev. Lett.*, vol. 59, no. 18, pp

[93] L. E. Ballentine, "The statistical interpretation of quantum mechanics," *Rev. Mod. Phys.*, vol. 42, no. 4, pp. 358–381, 1970.

[94] J. A. Wheeler and W. H. Zurek, *Quantum Theory and*

Measurement, Princeton University Press, 1983.

[95] W. H. Zurek, "Decoherence, einselection, and the quantum origins of the classical," *Rev. Mod. Phys.*, vol. 75, pp. 715–775, 2003.

[96] J. von Neumann, *Mathematical Foundations of Quantum Mechanics*, Princeton University Press, 1955.

[97] N. Bohr, "Can quantum-mechanical description of physical reality be considered complete?," *Phys. Rev.*, vol. 48, pp. 696–702, 1935.

[98] J. Etxezarreta Martinez, "Decoherence and Quantum Error Correction for Quantum Computing and Communications," arXiv:2202.08600 (2022).

[99] P. Shor, "Scheme for reducing decoherence in quantum computer memory," Phys. Rev. A 52, R2493 (1995).

[100] E. Knill and R. Laflamme, "Theory of quantum error-correcting codes," Phys. Rev. A 55, 900 (1997).

[101] P. Bej et al., "Creating quantum correlations in generalized entanglement swapping," Phys. Rev. A 106, 022428 (2022).

[102] A. Halimi et al., "Entanglement swapping and quantum correlations via symmetric joint measurements," Phys. Rev. Lett. 129, 030502 (2022).

[103] M. Arndt et al., "Wave–particle duality of C_{60} molecules," Nature 401, 680–682 (1999).

[104] K. Hornberger et al., "Theory of decoherence in a matter wave Talbot–Lau interferometer," Phys. Rev. A 67, 023601 (2003).

[105] M. Arndt and K. Hornberger, "Matter-wave interferometry with composite quantum objects," Nat. Phys. 10, 271–277 (2014).

[106] S. Nimmrichter, "Macroscopic matter-wave interferometry," Rev. Mod. Phys. 86, 307 (2014).

[107] O. Romero-Isart et al., "Large quantum superpositions and interference of massive nanometer-sized objects," Phys. Rev. Lett. 107, 020405 (2011).

[108] H. Carmichael, *An Open Systems Approach to Quantum Optics*, Springer (1993).

[109] J. Dalibard, Y. Castin, and K. Mølmer, "Wave-function approach to dissipative processes in quantum optics," Phys. Rev. Lett. 68, 580 (1992).

[110] S. Peng et al., "Quantum-trajectory-inspired Lindbladian simulation," PRX Quantum 6, 030358 (2025).

[111] F. Giacomini, E. Castro-Ruiz, and Č. Brukner, "Relativistic quantum reference frames: The operational meaning of spin," Nat. Commun. 10, 494 (2019).

[112] M. Lake and M. Miller, "Quantum reference frames, revisited," arXiv:2312.03811 (2023).

[113] T. Carette et al., "Operational quantum reference frame transformations," Quantum 9, 1680 (2025).