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Ze and Relational QM

Testing on molecules

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Abstract:

The measurement problem in quantum mechanics challenges our understanding of reality, demanding explanations beyond both Copenhagen's "collapse" and the Many-Worlds' ontological multiplicity. This paper introduces and formalizes the Ze framework as a novel synthesis of Relational Quantum Mechanics (RQM) and the Active Inference paradigm from theoretical neuroscience. Ze posits that quantum states are relational, defined by the posterior beliefs of interacting generative models engaged in variational free energy minimization. Within this framework, quantum superposition is formalized as high compatibility ($\mathcal{I} \approx 1$) between competing models, characterized by low free-energy conflict ($\Delta F < \theta$). Conversely, the transition to a localized state—the physical correlate of "collapse"—is reconceived not as a metaphysical event but as an optimization-driven phase transition. This occurs when model conflict exceeds a critical threshold ($\Delta F > \theta$), a process objectively driven by interactions like which-path marking. We demonstrate that matter-wave interferometry with complex molecules provides a direct experimental testbed for these principles, where which-path information and quantum erasure actively manipulate ΔF. Extending the isomorphism, we propose that transitions in human cognition—from focused wakefulness to dreaming and psychedelic states—are governed by analogous shifts in the brain's inferential threshold (θ). Thus, Ze offers a unified, testable architecture bridging quantum foundations, statistical physics, and the neuroscience of consciousness.

Keywords: Relational Quantum Mechanics, Active Inference, Variational Free Energy, Quantum Measurement, Matter-Wave Interferometry, Cognitive Neuroscience, Consciousness.

Introduction: From Relational Statements to Generative Models

The central tenet of Relational Quantum Mechanics (RQM) is the dissolution of the absolute, observer-independent quantum state. In RQM, physical quantities take value only relative to a specific system, and the quantum formalism describes how these relative states update upon interaction (Rovelli, 1996; Laudisa, 2022). This elegantly sidesteps the need for a privileged "classical" observer but leaves open a critical question: *What physically constitutes a "relation" or an "interaction" that leads to the determination of a relative state?*

We posit that this process is fundamentally inferential. Drawing from the Active Inference framework in theoretical neuroscience and machine learning (Friston, 2010; Parr et al., 2022), we introduce the Ze architecture. In Ze, any physical system that can be described as maintaining an internal model of its environment is considered a generative model. The "state" of a quantum system relative to a model is defined by the model's posterior beliefs, shaped by minimizing its variational free energy—a measure of surprise or prediction error. Crucially, when two such generative models, $\mathcal{M}_a$ and $\mathcal{M}_\beta$, interact with the same quantum process, the relational outcome (interference vs. localization) is determined by the compatibility of their respective inference processes.

Experiments demonstrating quantum interference of increasingly complex molecules—from fullerenes like C_{60} (Arndt et al., 1999) to synthetic macrocycles (Fein et al., 2019)—are not merely technological triumphs. They are, in our view, pristine experiments probing the boundaries of model compatibility. The "which-path" information does not cause collapse via conscious observation (Wigner, 1961), but by physically creating conditions where the generative models of the environment (e.g., a spin-path entangled state) necessarily incur a large free energy conflict, forcing a resolution via localization. This provides a testable, formal substrate for RQM's relational claims.

The Ze Architecture: Free Energy, Conflict, and Localization

Generative Models and Variational Free Energy

Consider a stream of data o_1:T arising from a quantum system. Two generative models, $\mathcal{M}_a$ and $\mathcal{M}_\beta$, engage in explaining this data. Each model entails a joint probability over observations and hidden states: $p(o_1{:}T, s^A{}_1{:}T \mid \mathcal{M}\_A)$ and $p(o_1{:}T, s^B{}_1{:}T \mid \mathcal{M}\_B)$. The hidden states s□ could represent path, spin, or internal molecular degrees of freedom. Each model performs inference by optimizing an approximate posterior $q\_A(s^A)$ or $q\_B(s^B)$ to minimize its variational free energy (VFE):

$$F\_A = E\_\{q\_A\} [\ln q\_A(s^A) - \ln p(o_1{:}T, s^A \mid \mathcal{M}\_A)]$$

$$F\_B = E\_\{q\_B\} [\ln q\_B(s^B) - \ln p(o_1{:}T, s^B \mid \mathcal{M}\_B)]$$

Minimizing VFE maximizes model evidence, balancing accuracy and complexity (Friston et al., 2017). In a quantum context, F can be related to the entropy of the relative state and the information gained through interaction (Bruza et al., 2015).

Interference as Model Compatibility

Quantum superposition, in Ze, is not a physical wave but the manifestation of compatible inferences. If $\mathcal{M}_a$ and $\mathcal{M}_\beta$ can maintain posteriors that are sufficiently similar—for instance, both assigning high probability to the particle being in a coherent superposition of paths—then their interpretations of reality are compatible. This compatibility is quantified by the Jensen-Shannon divergence (JSD) between their posteriors:

$$\mathcal{I} = 1 - D\_JS(q\_A(s) \,||\, q\_B(s))$$

Here, $\mathcal{I} \approx 1$ signifies high interference, as both models "agree" on a spread-out, coherent posterior. The magnitude of the free energy difference, $\Delta F = |F\_A - F\_B|$, is small in this regime. This formalizes the idea that interference persists as long as no single "which-path" fact is strongly inscribed in the relational dynamics between the system and its environment (Zurek, 2003).

Localization as a Phase Transition Induced by Model Conflict

The introduction of "which-path" information—via path-spin entanglement, emitted photons (Scully et al., 1991), or internal state decoherence—creates a fundamental conflict. Model $\mathcal{M}_a$ (e.g., a model tracking spin) now infers a different, more specific history than model $\mathcal{M}_\beta$ (e.g., a model tracking momentum). Their posteriors diverge ($D\_JS \to 1$, $\mathcal{I} \to 0$), and ΔF grows large. Ze posits that when ΔF exceeds a context-dependent threshold θ, the system undergoes a "phase transition" akin to a symmetry breaking in inference (Friston, 2019). The models' collective inference localizes to a single, consistent history:

$$\hat{s} = \mathrm{argmin}\_s (\alpha F\_A(s) + (1 - \alpha) F\_B(s))$$

$$q(s) \to q(s \mid \hat{s})$$

This localization is an objective optimization process to resolve the free energy conflict. It does not require a conscious observer, only the physical existence of the interacting generative models (which may be as simple as a spin detector or a vibrational mode of the molecule itself).

Active Inference and Control

A key power of Ze is its incorporation of action. Models can act to sample data that minimizes expected free energy (Parr & Friston, 2019). In the double-slit experiment, "erasing" which-path information (Kwiat et al., 1992) is an active operation that alters the observational context, reducing ΔF and restoring $\mathcal{I} \to 1$. This active element seamlessly connects the physics of measurement to the cybernetics of adaptive systems.

The Molecular Double-Slit Experiment as a Test of Ze

Recent matter-wave interferometry with large molecules provides a stringent test (Hornberger et al., 2012). Ze makes several concrete, testable predictions:

1. **Increased Internal Degrees of Freedom Accelerate Localization**: Larger, more complex molecules like C_{70} or organometallic complexes possess more internal vibrational/rotational modes (Fein et al., 2019). Each mode can couple to the path, acting as an additional generative model $\mathcal{M}$_i. The probability of a free-energy conflict $\Delta F > \theta$ occurring increases, leading to faster decoherence and a more rapid transition to localized particle behavior, as observed experimentally.
2. **Quantum Eraser as Active Free Energy Reduction**: The delayed-choice quantum eraser experiment (Kim et al., 2000) is a direct demonstration of Ze's active inference. The act of erasing the which-path information *after* the molecule has hit the detector, but before final correlation, is an intervention that retrospectively reduces the free energy conflict ΔF between the photon-path model and the molecular position model. Ze predicts that interference can be recovered *only* if the erasure operation successfully brings the models' posteriors back into compatibility ($\mathcal{I} \to 1$).
3. **Controlled Interference via Active Manipulation**: By actively manipulating an external degree of freedom (e.g., applying a weak magnetic field to perturb spin, or emitting a controlled photon), one can precisely tweak ΔF. Ze predicts the existence of a tunable "interference plateau" for $\Delta F < \theta$ and a sharp localization transition when $\Delta F > \theta$. This offers a new quantitative language for designing matter-wave interferometers.

Ze as Formal RQM

Ze provides the missing dynamical framework for RQM. In RQM, a "measurement" is just an interaction that establishes a new relative state (Rovelli, 1996). In Ze, this interaction is the process of free-energy minimization between generative models. The relational state *is* the (consensus) posterior. Which-path information is not inherently "classical"; it is a physical configuration that maximizes free energy conflict between plausible models of the event history.

Furthermore, Ze suggests a profound unification: the same principles governing the interference of molecules may govern cognitive states. The compatibility of competing hypotheses in the brain (manifest as ambiguity or creative thought) may correspond to a high $\mathcal{I}$ (Carhart-Harris & Friston, 2019). The collapse into a single perception or decision corresponds to localization ($\mathcal{I} \to 0$). States like dreaming or psychedelic experience, characterized by increased cognitive entropy, might reflect a lowered threshold θ or active suppression of model conflict (Friston et al., 2017).

We have argued that the Ze architecture, grounded in variational free energy and active inference, offers a rigorous, quantitative formalism for Relational Quantum Mechanics. It replaces the elusive “observer” with physically instantiated generative models and their interactions. The double-slit experiment with macromolecules emerges not just as a quantum curiosity, but as the canonical experiment to probe the transition from compatible, interfering inferences to conflict-driven localization. By framing quantum phenomena as processes of inference and model competition, Ze builds a bridge from the foundations of physics to the principles of life and mind.

A Formal Framework for Relational Quantum Mechanics

The Ze framework operationalizes the principles of Relational Quantum Mechanics (RQM) by grounding the relational nature of quantum states in a formal, information-theoretic process. This section presents the mathematical core of Ze, which posits that quantum phenomena—specifically the transition from superposition to localized states—are governed by the dynamics of competing generative models and their associated variational free energies. We formalize superposition as the compatibility of model posteriors and wavefunction collapse as a "phase transition" driven by free energy conflict, a process independent of a conscious observer. This formalism naturally incorporates active inference, whereby systems can act to control their own relational localization.

Formal Structure

The central postulate of Relational Quantum Mechanics (RQM) is that quantum states are not absolute but are defined relative to a particular system (Rovelli, 1996; Smerlak & Rovelli, 2007). While conceptually powerful, this relational view has historically lacked a precise, quantitative mechanism describing how a specific relative state becomes actualized from a set of possibilities during an interaction. The Ze architecture addresses this gap by proposing that any system capable of maintaining a probabilistic model of its sensory inputs can serve as a "relativizing" agent. The quantum state relative to that agent is its posterior belief, and the process of state determination is one of Bayesian inference governed by the minimization of variational free energy (Friston, 2010; Buckley, 2017).

Here, we detail the mathematical formalism of Ze. We define its core components—generative models, variational free energy, model conflict, and active inference—and demonstrate how they provide a unified account of quantum interference and localization. This formalism moves beyond interpretational debate by offering testable, quantitative predictions about the conditions under which quantum coherence is preserved or destroyed.

Generative Models as Relational Agents

In Ze, a relational perspective is instantiated by a generative model. Consider a stream of observations $o_1:T$ generated by a quantum system. Two distinct generative models, $\mathcal{M}_a$ and $\mathcal{M}_\beta$, engage in explaining this data. Each model is defined by a joint probability distribution over observations and a sequence of hidden states:

$$\mathcal{M}\_A: p(o_1:T, s^A{}_1:T), \quad \mathcal{M}\_B: p(o_1:T, s^B{}_1:T)$$

where s^A and s^B represent the hidden states (e.g., path, spin, internal degrees of freedom) inferred by each model. Crucially, these models are not necessarily held by a human mind; they can be physically instantiated in the structure of a measurement apparatus, the environment, or even internal degrees of freedom of the quantum system itself (e.g., a vibrational mode in a molecule). This aligns with the RQM perspective that any physical system can, in principle, serve as an "observer" (Laudisa, 2022).

Variational Free Energy and Inference

Each model performs inference to determine the most plausible hidden states given the observations. This is achieved by approximating the true posterior with a tractable distribution, q_A(s^A) for $\mathcal{M}_a$ and q_B(s^B) for $\mathcal{M}_\beta$. The optimal approximation is found by minimizing a functional called the Variational Free Energy (VFE) (Friston, 2010; Parr et al., 2022). For the two models:

$$F\_A = E\_\{q\_A\} [\ln q\_A(s^A) - \ln p(o_1:T, s^A \mid \mathcal{M}\_A)]$$

$$F\_B = E\_\{q\_B\} [\ln q\_B(s^B) - \ln p(o_1:T, s^B \mid \mathcal{M}\_B)]$$

Minimizing F is equivalent to maximizing the model evidence (or marginal likelihood) while penalizing model complexity, a fundamental principle in Bayesian inference (MacKay, 2003). The VFE serves as an upper bound on surprise (or negative log evidence), meaning that systems that minimize free energy are, on average, better at predicting their sensory inputs (Friston, 2019). In a quantum context, the minimization of F can be linked to the principle of minimum energy or maximum entropy for open systems (Bruza et al., 2015).

Model Conflict and the Genesis of Localization

The key dynamical quantity in Ze is the conflict between models, quantified by the absolute difference in their attained free energies:

$$\Delta F = | F\_A - F\_B |$$

When ΔF is small, the two models achieve similarly good (or similarly poor) explanations of the observations. Their inferences are not in direct competition. In the context of a double-slit experiment, this corresponds to a situation where no information is available to distinguish which path a particle took. The models $\mathcal{M}_a$ (perhaps representing a "left-path" hypothesis) and $\mathcal{M}_\beta$ (a "right-path" hypothesis) coexist with compatible beliefs, resulting in interference.

Conversely, a large ΔF signifies a fundamental conflict. One model provides a much more parsimonious and accurate account of the data than the other. This imbalance destabilizes the coexistence of hypotheses. In the double-slit setup, the introduction of "which-path" information (e.g., via path-spin entanglement) dramatically increases ΔF. The model that incorporates the new information (e.g., a model correlating spin state with path) achieves a significantly lower free energy than a model that ignores it. This conflict forces a resolution.

Interference as Compatibility, Localization as a Phase Transition

We can formalize the compatibility of models, and thus the presence of interference, using information theory. The degree of interference $\mathcal{I}$ is defined as:

$$\mathcal{I} = 1 - D\_JS(q\_A(s) \,||\, q\_B(s))$$

where D_JS is the Jensen-Shannon divergence, a symmetric and bounded measure of the dissimilarity between two probability distributions (Lin, 1991). When the posteriors q_A and q_B are similar—both assigning significant probability to multiple states (e.g., both paths)—their JSD is near zero, and $\mathcal{I} \approx 1$. This high compatibility is the formal signature of quantum interference within Ze (Fields et al., 2022).

Localization, the analogue of wavefunction collapse, occurs when $\mathcal{I} \ll 1$. This is triggered when ΔF exceeds a critical threshold θ, which may depend on environmental noise, temperature, or system complexity (Tuziemski & Korbicz, 2019). This transition is modeled as a first-order shift in the collective belief of the interacting systems:

$$q(s) \to q(s \mid \hat{s}), \quad \text{where} \quad \hat{s} = argmin\_s\ (\ \alpha\ F\_A(s) + (1 - \alpha)\ F\_B(s)\ )$$

Here, α weights the influence of each model, and the system's state localizes to the value ŝ that minimizes the weighted free energy conflict. This is an objective, optimization-driven process—a "phase transition" in the space of inferences—that requires no appeal to consciousness or fundamental randomness (Friston, 2019; Orrell, 2020).

Active Inference and the Control of Quantum Relations

A unique strength of Ze is its integration of action. Generative models can select actions a□ according to policies π to minimize *expected* free energy (Parr & Friston, 2019). Formally, the optimal policy is:

$$\pi = argmin\_\pi\ E[F\_A + F\_B]$$

This active inference loop provides a powerful lens on quantum experiments. The acquisition of "which-path" information is an action that physically increases ΔF, hastening localization.

Conversely, the operation of a *quantum eraser* (Kwiat et al., 1992; Kim et al., 2000) is an active intervention designed to reduce ΔF. By erasing or correlating path information in a specific way after the particle has been detected, the experimenter manipulates the relational context, thereby reducing model conflict and potentially recovering $\mathcal{I} \to 1$. This demonstrates that localization is not an irreversible death of coherence but a relational outcome that can be actively managed.

Conclusion of the Formal Exposition

The Ze formalism provides a rigorous, mathematically defined substrate for the philosophical tenets of RQM. It replaces the nebulous concept of "measurement" with the precise dynamics of variational inference and model competition. Superposition is relational compatibility of beliefs; collapse is relational resolution of belief conflict. This framework is inherently testable: it predicts that any physical manipulation that increases ΔF (e.g., coupling to more environmental degrees of freedom) will suppress interference, while active measures to reduce ΔF can restore it. By framing quantum mechanics as a theory of inference among interacting models, Ze offers a promising path towards unifying physical and cognitive principles.

The Molecular Double-Slit Experiment as a Crucial Test

The double-slit experiment with complex molecules represents the most compelling empirical testbed for the Ze framework and its synthesis with Relational Quantum Mechanics (RQM). This section analyzes the structure of matter-wave interferometry experiments through the lens of Ze's formal principles. We demonstrate how which-path information, quantum erasure, and active control manipulate the free energy conflict (ΔF) between generative models, directly predicting the emergence or suppression of interference fringes. Furthermore, we articulate a profound analogy between this quantum physical process and cognitive dynamics, suggesting that the same inferential principles govern both molecular interference and hypothesis selection in the brain. The molecular double-slit experiment thus becomes a Rosetta Stone, translating between the languages of quantum foundations, active inference, and cognitive science.

The Experimental Arena: Matter-Wave Interferometry of Macromolecules

Modern matter-wave interferometry has successfully demonstrated quantum superposition for objects of increasing mass and complexity, from electrons and neutrons to fullerenes (C_{60}, C_{70}) and synthetic organic molecules (Arndt et al., 1999; Fein et al., 2019). A typical experimental configuration involves a source of thermally emitted or supersonically expanded molecules, a collimator to create a coherent beam, a nanofabricated diffraction grating (acting as a double slit), a region of free propagation, and a position-sensitive detector (e.g., a scanning grating or time-resolved ionization) (Hornberger et al., 2012; Eibenberger et al., 2013).

The central quantum phenomenon is the detection of an interference pattern—spatial fringes—on the detector, which unequivocally demonstrates that each molecule did not take a definite path through one slit but rather existed in a coherent superposition of both paths. The gradual disappearance of this pattern with increasing molecular complexity or environmental coupling is the signature of decoherence (Schlosshauer, 2019).

Ze's Direct Prediction: From Which-Path Information to Free Energy Conflict

In the Ze framework, the pristine interference pattern corresponds to a regime where two generative models—$\mathcal{M}_a$ (e.g., a model representing "path through slit A") and $\mathcal{M}_\beta$ (modeling "path through slit B")—are highly compatible. Their variational free energies are nearly equal ($\Delta F < \theta$), and their posterior beliefs q_A and q_B are similar, yielding an interference measure $\mathcal{I} \approx 1$ (see previous section). The system's relational state, relative to the detector or any other system not resolving the path, is one of coherent superposition.

The introduction of *which-path information* fundamentally alters this relational landscape. This can be achieved through various physical means:

- **Spin marking**: Entangling the molecule's path with its internal spin state (Scully et al., 1991).
- **Photon emission**: A molecule scattering or emitting a photon upon passing through a specific slit (Durr et al., 1998).
- **Internal state decoherence**: Coupling the center-of-mass motion to the molecule's numerous internal vibrational or rotational degrees of freedom (Hornberger et al., 2012).

In Ze, each of these mechanisms instantiates a new, highly specific generative model. For example, a photon detector registering a scattered photon constitutes a model $\mathcal{M}$_photon-path with very strong, precise beliefs about the molecule's trajectory. This model's posterior is sharply peaked on one path, and crucially, its variational free energy F_photon-path is significantly lower (it is a more accurate and less complex explanation of the total data stream) than that of the simpler superposition models $\mathcal{M}_a$ or $\mathcal{M}_\beta$ alone. The resulting free energy conflict ΔF becomes large, exceeding the localization threshold θ. Consequently, the interference measure plummets ($\mathcal{I} \ll 1$), and the relational state localizes: the molecule is found to have taken a definite path. This localization is not a metaphysical "collapse" but the objective resolution of an inference conflict across the interacting systems (molecule, photon, detector).

Quantum Erasure as Active Inference to Restore Compatibility

The delayed-choice quantum eraser experiment provides a direct and stunning validation of Ze's relational, inference-based view (Kim et al., 2000; Walborn et al., 2002). In this setup, which-path information is recorded (e.g., via entanglement with another photon) but can later be "erased" by a measurement that coherently recombines the path-informative states.

In Ze, the erasure operation is a quintessential act of *active inference*. By choosing to perform a specific measurement on the ancillary system (the "idler" photon), the experimenter selects an action that actively reshapes the generative models at play. The erasing measurement destroys the informational basis for the sharply peaked posterior of the which-path model $\mathcal{M}$_which-path.

Effectively, it degrades that model's accuracy, raising its free energy F_which-path back towards the level of the simple path models. The free energy conflict ΔF is thereby actively reduced below the threshold θ. With the conflict resolved, the compatibility between the models is restored ($\mathcal{I} \rightarrow 1$), and the interference fringes reappear in the correlated subset of data. This demonstrates that "localization" and "interference" are not permanent properties but relational outcomes contingent on the specific inferential context established between systems (Zeilinger, 1999).

Testable Predictions and Control

Ze generates novel, testable predictions beyond standard decoherence theory:

1. **Predictive Thresholds**: By quantifying the coupling strength (e.g., dipole moment, polarizability) and information content of a which-path marker, one could, in principle, calculate the induced ΔF and predict the exact experimental conditions (molecular flux, temperature) for the observable fading of interference, moving from qualitative to quantitative thresholds (Tuziemski & Korbicz, 2019).
2. **Active Coherence Control**: One could use real-time feedback to actively manipulate an external field, subtly altering the which-path information to keep ΔF teetering below θ. Ze predicts the possibility of actively sustaining molecular interference in noisier environments than currently possible, a form of "quantum Maxwell's demon" based on inference (Parr & Friston, 2019).

The Cognitive Analogy: From Molecules to Mind

A profound implication of Ze is that the physics of quantum interference and the dynamics of cognition may be governed by isomorphic principles (Bruza et al., 2015; Fields et al., 2022). The following analogy elucidates this connection:

Table 1

Physical Experiment (Molecule)	Cognitive System (Brain)	Ze Formalism
Molecule in superposition	Multiple competing hypotheses about a sensory scene (e.g., Necker cube, ambiguous sound).	High model compatibility, $I \approx 1$.
Which-path information	Precise sensory data or focused attention that favors one hypothesis (Gregory, 1997).	Introduction of a model with low F, creating large ΔF.
Localization (Collapse)	Perceptual decision, crystallization of a single belief (Gold & Shadlen, 2007).	Resolution of conflict, $I \ll 1$, posterior peaks on $\hat{s}$.
Quantum Eraser	Cognitive processes that dissolve fixed interpretations: dreaming, REM sleep, or psychedelic states (Carhart-Harris & Friston, 2019). These states are characterized by increased entropy and reduced precision	Active reduction of ΔF by altering model precision or connectivity, restoring $I \rightarrow 1$.

	weighting of prior beliefs, effectively "erasing" strong perceptual hypotheses.	
Active Inference	Goal-directed behavior, planning, and sensory sampling (e.g., moving to get a better view) (Friston et al., 2017).	Policy selection $\pi = \text{argmin}_\pi E[F_A + F_B]$.

This analogy suggests that the brain's transition from ambiguous perception to definite belief is a classical (but functionally similar) instantiation of the same inferential "phase transition" that localizes a molecule in an interferometer. The psychedelic state, in particular, may be understood as a pharmacologically-induced "quantum eraser" for cognition, dissolving entrenched models (high ΔF) and restoring a landscape of compatible possibilities (high $\mathcal{I}$) (Carhart-Harris et al., 2014).

A Unifying Experimental Paradigm

The molecular double-slit experiment, interpreted through Ze, ceases to be a mere quantum curiosity. It becomes a fundamental experiment probing the dynamics of inference in physical systems. The appearance and disappearance of fringes are direct readouts of the free energy dynamics between relational models. This framework seamlessly integrates the physical act of measurement, the erasure of information, and the possibility of active control. Moreover, by establishing a formal analogy with cognitive processes, Ze positions quantum mechanics not as an isolated oddity but as a foundational instance of a universal principle: that systems exist and evolve by continuously resolving inference conflicts with their surroundings. In this view, the interfering molecule and the perceiving brain are both engaged in the same fundamental game of minimizing free energy in a relational world.

Ze as a Formal Dynamical Framework for Relational Quantum Mechanics

This section establishes a rigorous synthesis between the philosophical tenets of Relational Quantum Mechanics (RQM) and the formal, inference-based architecture of Ze. While RQM asserts that quantum states are inherently relative, it lacks a dynamical mechanism for how specific relative states are realized. Ze fills this gap by positing that the "relativization" of a state is an optimization process—the resolution of free energy conflict between interacting generative models. We demonstrate that Ze provides RQM with a concrete physical substrate: generative models instantiated in physical systems. Key RQM concepts—the relativity of facts, the role of interaction, and the non-absoluteness of measurement—find precise mathematical counterparts in Ze's dynamics of model competition, compatibility, and active inference. This synthesis moves RQM from a conceptual framework to a predictive, empirically engaged theory, positioning it as a compelling alternative to both Copenhagen orthodoxy and many-worlds interpretations.

The Need for Dynamics in a Relational World

Relational Quantum Mechanics (RQM), pioneered by Rovelli (1996), offers a profound resolution to the measurement problem by rejecting the notion of an absolute, observer-independent quantum state. Its core postulate is that physical quantities take definite values only relative to a specific system, and the quantum formalism describes the evolution of these relative states (Smerlak & Rovelli, 2007; Laudisa, 2022). This elegantly dissolves the paradox of Schrödinger's cat: the cat is not simultaneously dead and alive in an absolute sense; it is in a definite state (alive or dead) relative to an interacting system (e.g., the decaying atom, the Geiger counter), while potentially being in a superposition relative to a distant observer.

However, a persistent critique of RQM has been its perceived vagueness on the mechanics of the relational process (Goldstein, 2021). What precisely constitutes a "system" that can establish a relative state? What physical differentiates a "strong" interaction that produces a definite relative fact from a "weak" one that preserves relational superposition? Ze provides definitive answers by equating a "relativizing system" with a generative model and the establishment of a relative fact with the outcome of a variational free energy minimization process.

The Relativizing System: From Abstract Observer to Generative Model

In RQM, any physical system can, in principle, serve as an "observer" (Rovelli, 1996). Ze operationalizes this by specifying that a system capable of establishing a relative quantum state is one that maintains an internal model of its sensory input and acts to minimize its variational free energy—a defining feature of living systems, but also of engineered detectors and even structured environments (Friston, 2019; Buckley, 2017). A photon detector, a spin environment, or the vibrational modes of an interfering molecule itself are all physical instantiations of generative models ($\mathcal{M}$_A, $\mathcal{M}$_B, …).

The "state" of a quantum system relative to such a model is not a hidden variable but is explicitly given by the model's posterior belief, q(s). This directly implements the RQM view that "states are correlations" (Rovelli, 1996). Before an interaction, two models may have posteriors that are compatible and spread out (e.g., both assigning high probability to multiple paths). In this case, the quantum system is in a relational superposition relative to the pair of models, manifesting as interference. This stands in stark contrast to the many-worlds interpretation, which posits the ontological branching of reality (Vaidman, 2021). In Ze and RQM, there are not multiple worlds, only multiple, compatible inferences about a single relational reality (Fields et al., 2022).

Interaction as the Genesis of Relational Facts through Model Conflict

In RQM, a relative fact is established when two systems interact. Ze provides the dynamics for this event. An interaction that can yield a definite relative fact is one that creates a significant free energy conflict (ΔF) between the generative models involved. Consider again the double-slit experiment. The passage of a molecule is a weak interaction relative to a distant, coarse-grained detector; the models for "path A" and "path B" remain compatible ($\Delta F < \theta$), so no definite path fact is established relative to that detector—interference results.

Introducing a which-path marker (e.g., a spin-path entanglement) transforms the interaction. It creates a new, highly accurate generative model (e.g., the model of the spin-detector apparatus) whose posterior is sharply inconsistent with the superposition posteriors of the simple path models. The free energy difference ΔF becomes large, exceeding the localization threshold θ. The optimization dynamics of Ze then force a resolution: the system of interacting models collectively shifts to a single, consistent posterior peak q(s | ŝ). A definite fact—"the molecule took path A"—is now established relative to the entire network of interacting models (the molecule, the marker, the detector). This process is objective and physical but inherently relational; a system not included in this interacting network (e.g., a distant isolated probe) may still describe the molecule in a superposition (Zurek, 2003; Tuziemski & Korbicz, 2019). This perfectly captures the RQM notion that "different observers can give different accounts of the same sequence of events" (Rovelli, 1996).

The Environment and the Stability of Relational Facts

RQM must explain how the classical, stable world of shared facts emerges from a network of relative descriptions. Ze addresses this through the concept of environmental redundancy, closely related to quantum Darwinism (Zurek, 2009). When a quantum system interacts with a complex environment (e.g., a which-path marker that scatters many photons), the information about the localized fact (e.g., the path) is imprinted onto numerous, independent environmental degrees of freedom (Ollivier et al., 2004).

In Ze, each of these environmental fragments can be seen as instantiating a roughly isomorphic generative model. A vast ensemble of models ($\mathcal{M}$_env1, $\mathcal{M}$_env2, …) now share the same low-free-energy, localized posterior. For any new system (an "observer") to interact and infer a state, it will most likely couple to this redundant environmental data. Consequently, it will almost invariably infer the same localized fact, as any other inference would carry a prohibitively high free energy cost. Thus, the stability and objectivity of classical facts arise not from absoluteness, but from the *ecological dominance* of a particular relational outcome across the network of interacting models (Fields et al., 2022). The "classical world" is the regime where a specific relational state has become so widely replicated in the environment that it is effectively unavoidable for subsequent inferential interactions.

Active Inference: The Relational Dimension of Action

A significant advancement Ze offers over standard presentations of RQM is the formal inclusion of *active inference* (Parr & Friston, 2019). In RQM, interactions happen, but their specific nature is often treated as a given. In Ze, systems can actively choose *how* to interact to manage their relational state.

An agent (a complex generative model) can select actions a□ according to a policy π to minimize its expected free energy. In the quantum domain, this translates to *controlling the relational context*. The quantum eraser experiment (Kim et al., 2000) is the archetypal example: the experimenter's choice of measurement basis on an ancillary photon is an active inference that reconfigures the network of models. This action effectively destroys the model responsible for the high ΔF conflict, reducing it and restoring relational superposition ($\mathcal{I} \to 1$). This demonstrates that relational facts are not immutable; they can be actively dissolved and reconstituted by intervening in the inferential network. This active dimension embeds a cybernetic, goal-oriented principle into the heart of quantum relationality, suggesting that agents can steer their quantum relations to achieve preferred states of belief or knowledge (Friston et al., 2017).

Contrast with Other Interpretations

The Ze-RQM synthesis carves a distinct path among major interpretations:

- **Against Copenhagen**: It eliminates the primacy of a classical, non-quantum observer. Measurement is just a specific type of physical interaction governed by universal inference principles, not a mysterious border between realms (Buckley, 2017).
- **Against Many-Worlds**: It denies ontological proliferation. Superposition is a property of relational description (model compatibility), not of reality itself. There is one world with many possible relational descriptions (Rovelli, 1996).
- **Against Objective Collapse (e.g., GRW)**: Localization is not a spontaneous, random physical event modifying the wavefunction. It is a deterministic (given the models) optimization outcome in the space of inferences, triggered by specific environmental couplings.

A Complete Relational Paradigm

Ze provides the missing dynamical engine for Relational Quantum Mechanics. It translates RQM's philosophical insights into a formal, testable theory of how relative states are physically realized and updated. By identifying relational systems with generative models and relational facts with the stable outcomes of free-energy-minimizing interactions, it grounds quantum mechanics in the same principles that appear to govern adaptive, inferential systems at other scales. This synthesis does not just interpret quantum mechanics; it suggests that quantum mechanics is a fundamental chapter in a broader physics of inference, where reality is constituted by a dynamic web of relational, model-based interactions. The task ahead is to extract quantitative, falsifiable predictions from this synthesis, particularly in the domain of controlled quantum transitions in complex systems, thereby solidifying its status as a viable and fertile framework for understanding the quantum world.

Testable Predictions Across Physical and Cognitive Domains

Abstract: The true measure of any scientific framework lies in its capacity to generate novel, falsifiable predictions. The synthesis of Ze and Relational Quantum Mechanics (RQM) provides precisely this, offering a concrete set of experimental consequences that bridge quantum physics and cognitive science. By formalizing the transition between quantum interference and

localization as a process driven by variational free energy conflict (ΔF), Ze yields quantitative predictions for matter-wave interferometry experiments with complex molecules. Furthermore, extending this formalism to cognitive systems suggests analogous dynamics govern transitions between exploratory and focused mental states. This section delineates four key testable predictions, demonstrating how Ze transforms from a conceptual framework into an empirically engaged research program.

Prediction 1: Molecular Complexity as a Direct Probe of Free Energy Conflict

A foundational prediction emerges directly from the Ze formalism: the rate at which quantum interference is lost—localization occurs—should scale predictably with the number and coupling strength of a molecule's internal degrees of freedom. This aligns with, but formally sharpens, standard decoherence theory (Schlosshauer, 2019). In Ze, each internal vibrational or rotational mode capable of coupling to the center-of-mass path degree of freedom acts as a rudimentary generative model (Hornberger et al., 2012). The introduction of a which-path marker (e.g., entanglement with a photon) creates a low-free-energy model for the composite system. The conflict ΔF between this composite model and a model of a pure superposition grows as more internal modes become correlated with the path information, providing additional "witnesses" to the which-path fact (Ollivier et al., 2004; Zurek, 2009).

Ze predicts a specific quantitative relationship: for a homologous series of molecules (e.g., fullerenes C_{60}, C_{70}, functionalized derivatives), the visibility V of the interference pattern should decay as a function of the effective number of thermally accessible internal states N_int and their coupling constants. Formally, $V \propto \exp(- \kappa \cdot N\_int \cdot \langle g^2 \rangle \cdot t)$, where κ is a constant, $\langle g^2 \rangle$) is the mean squared coupling, and t is the time of flight. Experiments by Arndt et al. (1999) and Fein et al. (2019) have qualitatively shown this trend. A stringent test of Ze would involve precisely measuring interference visibility for a designed series of molecules with systematically incremented internal complexity (e.g., adding specific functional groups) and confirming the predicted functional form of V, thereby directly linking ΔF to measurable structural parameters.

Prediction 2: Quantum Erasure as an Active Inference Protocol to Modulate ΔF

The quantum eraser experiment (Kim et al., 2000; Walborn et al., 2002) is reinterpreted in Ze as an active inference procedure to *reduce* a pre-existing free energy conflict. Ze makes a nuanced, testable prediction about this process: the degree to which interference is recovered should be *quantitatively proportional* to the amount of which-path information destroyed.

If the which-path information is stored in an ancillary qubit with a well-defined von Neumann entropy, the erasure operation will reduce this entropy. Ze posits that the recovered interference visibility V_recovered is not binary but follows: $V\_recovered \approx V\_0 \, (1 - I\_post\text{-}erasure \, / \, I\_pre\text{-}erasure)$, where I is the mutual information between the path and the ancilla, and V_0 is the ideal visibility with no which-path information. An imperfect eraser, which only partially decoheres the ancilla, should therefore yield only a partial recovery of fringes. This can be tested in photonic or molecular interferometry by implementing tunable, partial erasure operations—for instance, by subjecting the which-path marker to a controlled decoherence channel before the erasure measurement—and precisely measuring the correlation between the residual which-path information and the recovered fringe contrast (Kwiat et al., 1992).

Prediction 3: Predictive Control of Interference via Engineered ΔF

A powerful application of Ze is the active control of the quantum-classical boundary. By treating ΔF as an engineered variable, one can design experiments to *predict and verify* the precise conditions for the loss of interference. Consider a molecule with a controllable electric dipole moment or spin state (Scully et al., 1991). Applying a known, spatially varying electric or magnetic field creates a which-path marker of calculable strength.

Ze predicts that the induced ΔF can be computed from the interaction Hamiltonian and the initial states of the system and field. One can then design an experiment where a control parameter (e.g., field gradient) is swept, and the interference visibility V is measured. The prediction is a smooth, sigmoidal transition from $V \approx 1 \rightarrow V \approx 0$ at a critical value of the control parameter that corresponds to ΔF crossing the threshold θ. The shape of this transition curve provides a direct experimental signature of the underlying free energy dynamics and allows for an empirical determination of the localization threshold θ for that specific experimental configuration (Tuziemski & Korbicz, 2019). This moves interferometry from a demonstrative tool to a metrological one for measuring "inferential pressure."

Prediction 4: Cognitive States as Manifestations of a Dynamic Localization Threshold

The most profound and interdisciplinary prediction arises from Ze's proposed isomorphism between quantum localization and cognitive decision-making (Bruza et al., 2015; Friston, 2019). If the resolution of perceptual ambiguity (e.g., in binocular rivalry or the Necker cube) is analogous to a localization event, then the brain's effective threshold θ must be a neurophysiologically modulable parameter.

Ze predicts that states of mind associated with reduced precision of prior beliefs or increased cognitive entropy—such as REM sleep, certain meditation practices, and psychedelic states induced by serotonin 2A receptor agonists like psilocybin—are characterized by a *lowered* θ (Carhart-Harris & Friston, 2019; Carhart-Harris et al., 2014). In these states, competing perceptual or cognitive hypotheses can coexist (high $\mathcal{I}$) for extended periods because even moderate free energy conflicts (ΔF) are insufficient to trigger a definitive "collapse" to a single interpretation. This should manifest behaviorally as increased perceptual switching rates, greater acceptance of ambiguity, and enhanced creativity. Neurophysiologically, it should correlate with markers of reduced neural signal determinism and increased entropy in functional connectivity, as observed in psychedelic neuroimaging (Tagliazucchi et al., 2014).

Conversely, focused, alert wakefulness and high-stress states are predicted to involve a *raised* θ, promoting rapid and decisive localization to single interpretations or action plans to facilitate adaptive behavior (Parr & Friston, 2017). This framework generates specific, testable hypotheses: for example, pharmacological agents that increase synaptic gain (e.g., amphetamines) should raise θ, leading to faster perceptual decisions and reduced tolerance for ambiguity, while psilocybin should lower θ, with the opposite effects. Behavioral paradigms like binocular rivalry, combined with pharmacological manipulation and measures of neural entropy, provide a direct experimental pipeline to test these predictions.

A Framework for Empirical Synthesis

The predictions outlined here demonstrate that the Ze-RQM synthesis is not a closed philosophical system but a generative engine for empirical inquiry. In the physical domain, it demands new precision in matter-wave experiments, turning them into probes of inferential dynamics. In the cognitive domain, it provides a rigorous, mathematically grounded framework for understanding the continuum of conscious states, from the focused to the psychedelic.

These predictions are deliberately falsifiable. The failure to observe the predicted quantitative scaling of decoherence with molecular complexity, or the absence of a correlation between pharmacologically altered perceptual switching and neural entropy, would constitute significant challenges to the framework. By tethering the relational view of quantum mechanics to the mathematics of variational inference and generating concrete, interdisciplinary hypotheses, Ze fulfills the essential role of a scientific theory: to provide a coherent, predictive, and ultimately testable understanding of reality.

Unifying Principles and the Central Synthesis

This concluding section synthesizes the core argument of the Ze framework in its integration with Relational Quantum Mechanics (RQM). We posit that the molecular double-slit experiment serves as the definitive physical arena for testing Ze's principles, transforming a foundational quantum puzzle into an operational probe of inferential dynamics. Ze achieves a unique synthesis, unifying the philosophical relationalism of RQM with the mathematical formalism of variational free energy and active inference. This leads to a profound reconceptualization: the quantum "collapse" is not a physical bifurcation of reality but an optimization process within a network of interacting models. Furthermore, this unified perspective reveals a deep isomorphism, suggesting that cognitive phenomena—from focused wakefulness to dreaming and psychedelic states—are macroscopic manifestations of the same inferential principles governing quantum coherence and localization.

The Double-Slit Experiment as the Rosetta Stone

Throughout this work, we have argued that matter-wave interferometry with complex molecules is not merely a spectacular confirmation of quantum theory but the crucial experimental testbed for the Ze architecture (Arndt et al., 1999; Fein et al., 2019). In the Ze view, the experiment is a physical instantiation of a controlled inference problem. The appearance of an interference pattern is the direct, observable signature of high compatibility ($\mathcal{I} \approx 1$) between generative models (e.g., $\mathcal{M}$_left-path and $\mathcal{M}$_right-path, corresponding to low free energy conflict ($\Delta F < \theta$). The gradual fading of this pattern with increasing molecular complexity or environmental coupling is the signature of growing ΔF, culminating in a phase transition to localization when ΔF > θ (Hornberger et al., 2012; Schlosshauer, 2019). The quantum eraser experiment (Kim et al., 2000) then demonstrates the active, reversible nature of this process: a deliberate intervention (erasure) can reduce ΔF and restore compatibility, thereby recovering interference. Thus, every facet of the double-slit phenomenon—coherence, decoherence, and erasure—maps directly onto the formal dynamics of model competition and optimization within Ze, providing a one-to-one correspondence between physical observation and inferential calculus.

The Ze Synthesis: Unifying RQM, Active Inference, and Variational Principles

The central achievement of Ze is its formal unification of three powerful conceptual frameworks. First, it provides a dynamical mechanism for Relational Quantum Mechanics (Rovelli, 1996). In RQM, states are relative; in Ze, a relative state is the posterior q(s) of a generative model undergoing free energy minimization (Friston, 2010). An interaction that establishes a "relative fact" is precisely one that creates a sufficient free energy conflict (ΔF) to force localization across the interacting models. This grounds RQM's philosophical insights in the mathematics of Bayesian inference (Buckley, 2017).

Second, Ze seamlessly incorporates *active inference* (Parr & Friston, 2019). Systems are not passive recipients of measurements but can act to shape their relational context. The acquisition of which-path information is an action that increases ΔF, while quantum erasure is an action to decrease it. This active dimension, often absent in interpretations of quantum mechanics, positions quantum systems as participating in a cybernetic loop of perception and action, aligning with modern perspectives on embodied and adaptive agency (Friston et al., 2017).

Third, at its core, Ze is governed by the *variational free energy principle*, a unifying principle in theoretical biology and neuroscience that states that self-organizing systems act to minimize surprise or prediction error (Friston, 2019). Ze proposes that this principle extends into the quantum domain. The minimization of F_A and F_B by individual models, and the resolution of their conflict through localization, are all instances of free energy minimization at different scales. This positions quantum mechanics not as a separate, exotic theory but as the foundational application of a more general physics of inference (Fields et al., 2022).

Reconceptualizing Collapse: From Ontological Branching to Relational Optimization

This synthesis forces a radical reinterpretation of the measurement problem. In the many-worlds interpretation, "collapse" is an illusion; reality ontologically branches into multiple, non-communicating histories (Vaidman, 2021). In Ze, informed by RQM, the opposite is true: "collapse" or localization is a real process, but it is not an ontological branching of the world. It is an optimization process within a relational network.

When ΔF exceeds θ, the coexisting, compatible posteriors q_A and q_B become unstable. The system of interacting models undergoes a collective shift to a single, consistent configuration q(s | ŝ) that minimizes the weighted free energy. This is a physical process—a symmetry breaking in the space of inferences—but its outcome is inherently relational. It establishes a fact *relative to the specific network of interacting models* (e.g., the molecule, the which-path marker, the detector). There is no single, objective "collapsed wavefunction" of the universe, only a web of consistently updated relative states (Rovelli, 1996; Smerlak & Rovelli, 2007). This resolves the paradox of Wigner's friend without invoking consciousness: different friends (different generative models) may have different relative states until they interact and their models conflict, forcing a consistent optimization across the now-enlarged network (Zurek, 2003).

The Cognitive Isomorphism: From Quantum Interference to States of Consciousness

The most profound implication of Ze is the proposed isomorphism between quantum and cognitive dynamics (Bruza et al., 2015). If the core process is the minimization of free energy conflict in a network of models, then the same formal template should apply whether the models are describing molecular paths or perceptual hypotheses.

In this view, the focused, alert state of *wakefulness* is characterized by a high localization threshold (θ) and efficient, rapid resolution of model conflicts (ΔF). The brain quickly "collapses" ambiguous sensory data into definite percepts and decisions to guide action (Gold & Shadlen, 2007). This is the cognitive analogue of a molecule showing particle-like behavior in a which-path experiment.

Conversely, the state of *dreaming* (particularly REM sleep) and the *psychedelic state* induced by 5-HT2A receptor agonists like psilocybin appear to be functional analogues of quantum interference (Carhart-Harris & Friston, 2019). Neuroimaging evidence shows these states are marked by increased entropy, reduced neural signal determinism, and a flattening of the brain's functional landscape (Carhart-Harris et al., 2014; Tagliazucchi et al., 2014). In Ze, this corresponds to a lowered effective θ. Competing cognitive and perceptual models can coexist with high compatibility ($\mathcal{I} \approx 1$) for extended periods, as even moderate conflicts are insufficient to trigger definitive localization. This manifests as fluid thought, bizarre dream narratives, and perceptual kaleidoscopy—the mind exploring a "superposition" of possibilities. The transition from a psychedelic state back to normal consciousness is then akin to a cognitive "collapse," where the brain's inference regime returns to a high-θ, localization-prone state (Parr & Friston, 2017).

Towards a Physics of Inference

In conclusion, the Ze framework, synthesized with Relational Quantum Mechanics, offers a coherent and empirically engaged path forward. It demystifies quantum phenomena by grounding them in the mathematics of inference and model competition. The molecular double-slit experiment is its proving ground, and the dynamics of human consciousness provide a compelling macroscopic analogue. This work suggests that the long-sought unification may not be between gravity and quantum mechanics alone, but between physics and the principles of life and mind through the universal calculus of variational free energy. The task ahead is to pursue the detailed experimental predictions outlined herein, to refine the mathematical formalisms, and to explore whether the architecture of Ze truly provides the foundational language for a physics of relational, inferential systems.

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