The Theory of Observerhood in Quantum Measurement: A Trial Formulation of Basis Selection Based on Informational-Geometric Consistency

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Abstract：

This study proposes a reformulation of the observer's role in quantum measurement by introducing an informational structural parameter ϕ, referred to as *observerhood* (SOP). Through this framework, the measurement problem is reframed not as a causal question—"why does collapse occur?"—but as a structural one: "why does this informational structure stabilize coherently?"

The observer is modeled as an informational agent characterized by an exponential-family state ρ_ϕ defined over a set of measurable operators $\{A_i\}$. The informational consistency between the quantum state ρ and the observer's structure ϕ is quantified by the quantum relative entropy $C(\rho,\phi)=-S(\rho\|\rho\phi)$.
The gradient flow of this function yields a non-unitary informational update process of the observer's structure.
In a spin-½ system, the stationary distribution $\mu\_eq(\phi)$ reconstructs the Born rule in the limit of low informational temperature.

While the present theory does not claim novel empirical predictions, it reformulates measurement as a *dual process* of external decoherence and internal consistency. In doing so, it provides a structural foundation that unifies decoherence theory, relational quantum mechanics, and informational structural realism.
The notion of *observerhood* is generalized beyond consciousness, encompassing devices, artificial agents, and biological systems, thus bridging quantum foundations, information geometry, and cognitive science through a common structural perspective.

1.Introduction

The measurement problem in quantum mechanics embodies the fundamental question of how a quantum state gives rise to a definite classical outcome.
Although numerous interpretations—such as the many-worlds hypothesis, decoherence theory, QBism, and relational quantum mechanics—have been proposed, there remains no unified view regarding how to formally describe the role of the observer.

This paper treats the observer as an *informational structure*, and proposes a framework in which measurement is described as an *informational-geometric alignment* between the quantum state ρ and the observer's structural parameter ϕ.
Through this approach, the observer's active contribution—its meaning structure, preference, and internal organization—can be quantified while maintaining consistency with the probabilistic structure of standard quantum mechanics.

The present theory does not compete with decoherence theory.
Rather, it presupposes the *external stabilization* of a system through environmental interaction, and seeks to describe how an observer, upon receiving such stabilized information, *internally integrates* it as an experience.
In this sense, while external decoherence concerns the *physical stabilization of the basis*, the present approach addresses the *informational stabilization within the observer*.
Measurement, therefore, is conceived as a two-fold process: external decoherence and internal consistency.

2. Theoretical Framework

2.1 Definition of Observerhood (SOP)

Observerhood—or *Structural Observer Parameterization (SOP)*—refers to an informational parameter $\phi \in \Theta$ that represents the internal informational structure of an observing agent (human, device, or AI).
The parameter ϕ specifies which informational features (operator directions) the agent interprets as *consistent* or *meaningful*.
Observerhood does not presuppose consciousness; it is applicable to any informational agent capable of maintaining structural coherence, including physical measurement apparatuses and artificial systems.

2.2 Exponential-Family States and the Consistency Function

For a given observer structure ϕ, define the corresponding exponential-family state as

$$\rho_\phi = \exp\left(\sum_i \phi_i A_i - \psi(\phi)\right), \quad \psi(\phi) = \log \mathrm{Tr}\, \exp\left(\sum_i \phi_i A_i\right)$$

Here, $\{A_i\}$ denotes the set of observables regarded as *measurable* for the observer, given externally by the physical configuration of the measurement context.

The *consistency function* is defined in terms of the quantum relative entropy as

$$C(\rho, \phi) = -S(\rho|\rho_\phi) = -\mathrm{Tr}\big[\rho\big(\log\rho - \log\rho_\phi\big)\big]$$

$C(\rho,\ \phi)$ measures the *informational proximity* between ρ and ρ_ϕ; larger values correspond to greater informational consistency between the quantum state and the observer's structure.

2.3 Consistency Dynamics

The temporal evolution of observerhood ϕ is expressed as a stochastic gradient flow:

$$d\phi = -\nabla_\phi C(\rho, \phi)\, dt + 2D\, dW_t$$

where D > 0 denotes the *informational diffusion coefficient* (informational temperature) and W_t represents a Wiener process.
The corresponding Fokker–Planck equation is

$$\frac{\partial\mu}{\partial t} = \nabla_\phi \cdot \big(\mu\, \nabla_\phi C(\rho, \phi)\big) + D\, \nabla_\phi^2 \mu$$

Its stationary solution is given by

$$\mu_{\mathrm{eq}}(\phi_i) \propto exp\left(\frac{C(\rho, \phi_i)}{D}\right)$$

$\mu_$eq(ϕ) is not to be interpreted as a probability distribution but as a *consistency weight* that reflects the degree to which each informational structure ϕ stabilizes with respect to ρ.

3.Worked Example: Qubit

3.1 Setup

Consider a two-level system described by

$$\rho = \frac{1}{2}(I + \vec{r}\cdot\vec{\sigma}), \quad \rho_\phi = \frac{1}{2}(I + \vec{n}\cdot\vec{\sigma})$$

where ***r*** and ***n*** are vectors on the Bloch sphere, and σ denotes the Pauli matrices. Let the angle between ***r*** and ***n*** be $\boldsymbol{\gamma}$, such that

$$\cos\gamma = \vec{r}\cdot\vec{n}$$

This angle becomes the main variable determining the informational consistency $C(\rho, \phi)$.

3.2 Explicit Form of the Consistency Function

Direct computation yields

$$C=-\frac{1}{2}(1+\vec{r}\cdot\vec{n})\log\frac{1+\vec{r}\cdot\vec{n}}{1+|\vec{n}|}-\frac{1}{2}(1-\vec{r}\cdot\vec{n})\log\frac{1-\vec{r}\cdot\vec{n}}{1-|\vec{n}|}$$

The function attains its maximum at $\boldsymbol{n}=\boldsymbol{r}$,corresponding to perfect informational alignment between the quantum state and the observer's structure.

3.3 Stationary Consistency and Low-Temperature Expansion

The stationary consistency weight is given by

$$\mu_{\text{eq}}(\phi)\propto\exp\left(\frac{C(\rho,\phi)}{D}\right)$$

In the low-temperature (small-*D*) limit, the dominant term depends on $\boldsymbol{r}\cdot\boldsymbol{n}=\mathbf{cos}\gamma$.
For a discrete set of orientations$\{\phi i\}$,

$$\mu_{\text{eq}}(\phi_i)\propto\exp\left(\frac{\vec{r}\cdot\vec{n_i}}{D}\right)\approx\text{const}\cdot(1+\alpha\cos\gamma_i)$$

where $\alpha\sim D-1$.

After normalization, one obtains

$$P(\phi_i)\approx\frac{1+\cos\gamma_i}{2}=|\langle\psi|\phi_i\rangle|^2$$

This reproduces the Born rule as a reconstruction from the informational-geometric consistency potential.
The Born probabilities thus emerge as equilibrium weights associated with structurally stabilized observer states rather than as primitive postulates.

4.Comparative Analysis

4.1 Complementarity with Decoherence Theory

Decoherence theory explains how quantum systems lose interference through environmental interaction and thereby display classical probabilistic behavior.
The stable bases selected by the environment are known as *pointer bases*, which determine the effective classical stability of macroscopic behavior.
According to Zurek (2003), such environment-induced entanglement produces a "for all practical purposes" collapse, even without invoking an observer.

The present theory accepts this external process as a prerequisite, and focuses instead on describing the *internal consistency process* within the observer.
Measurement is thus understood as a dual process:
(i) *external stabilization* through environment–system interaction, and

(ii) *internal stabilization* through the informational structure of the observer.
The former selects physically stable bases, while the latter determines how such bases are integrated and stabilized as *experienced structure*.
The two are not in conflict but are complementary aspects of one coherent process.

4.2 Comparison with Other Interpretations: QBism, Relationalism, Many-Worlds

QBism (Quantum Bayesianism) interprets measurement probabilities as subjective updates of belief by an observer.
The present framework partially inherits this interpretive stance but replaces *belief* with *structural consistency*.
Here, observerhood ϕ does not represent a mental or conscious state but the *informational organization* of an observing system.

Relational Quantum Mechanics (Rovelli, 1996) defines states only in relation to other systems.
Similarly, this framework assumes relationality but further formalizes *which relations stabilize as consistent* through an informational-geometric potential $C(\rho,\phi)$.
Whereas RQM leaves the stability condition implicit, the present model provides an explicit criterion for relational fixation.

The Many-Worlds interpretation (Everett) retains all possible branches equally.
In contrast, this theory introduces a natural selection mechanism through the maximization of $C(\rho,\phi)$: the observer's structure stabilizes one informationally coherent branch among the manifold of possibilities.
The resulting framework therefore describes the observer's world-line as a self-consistent branch within the global superposition.

4.3 Connection with IIT and the Free Energy Principle

Tononi's *Integrated Information Theory* (IIT) quantifies the degree of consciousness by a scalar Φ representing the extent of informational integration.
In the present framework, the consistency function $C(\rho,\phi)$ can be interpreted as a *structural potential* that specifies the direction of integration rather than its quantity.
While Φ measures internal coupling strength, $C(\rho,\phi)$ measures the *informational congruence* between the internal model and the external state.
Combining both allows a unified description of the *internal integration* and *external alignment* of observerhood.

Friston's *Free Energy Principle* (FEP) posits that self-organizing systems evolve to minimize variational free energy F.
Formally, the stochastic gradient flow

$$d\phi = -\nabla_{\phi} C(\rho,\phi)\, dt + 2D\, dW_t$$

can be regarded as the minimization of *negative free energy*,
highlighting a structural correspondence with FEP.
Whereas the FEP emphasizes prediction-error minimization, the present approach characterizes the observer as maximizing *consistency potential*—that is, stabilizing the world not through prediction, but through structural coherence.

4.4 Structural Reorientation

From these correspondences, the measurement problem can be reoriented from a *causal explanation of physical collapse* to a *stability condition of informational structure*.
Introducing observerhood enables quantum theory to be reformulated within the framework of *structural realism*:
measurement is no longer the selection of an outcome, but the stabilization of consistency.

5.Verification & Conceptual Contribution

The present theory yields the same statistical predictions as standard quantum mechanics. As long as the set of measurable operators $\{Ai\}$ remains identical, the distribution of measurement outcomes is indistinguishable from that of orthodox QM.

Its contribution does not lie in proposing novel empirical results but in *reconstructing the measurement process* as an informational-geometric alignment between the observer's structure ϕ and the quantum state ρ.
This reconstruction provides a new conceptual layer to the interpretation of quantum measurement, focusing on *consistency stabilization* rather than physical collapse.

5.1 AI Observer Simulation

The proposed model can be tested through simulation using reinforcement-learning systems or neural networks as artificial observers.
By evaluating the gradient flow of $C(\rho,\phi)$ before and after task learning, and examining the change in operator preferences $\{Ai\}$,
one can quantify how the learning structure correlates with observerhood.
Such experiments would allow the notion of observerhood to be instantiated within machine-learning architectures, demonstrating the informational dynamics of internal consistency.

5.2 Visualization of Consistency

The stationary consistency distribution $\mu\text{eq}(\phi)$ can be visualized on the Bloch sphere as a heat map.
By varying the informational temperature（for example, D=0.1,0.5,1.0）, the sharpness of alignment can be compared, illustrating how internal noise within the observer affects the

concentration of consistency weights.
This visualization provides an intuitive depiction of the trade-off between structural stability and informational diffusion.

5.3 Consistency with Standard Theory

No claims are made that contradict standard quantum mechanics.
Even if apparent differences arise between measurement devices, these can be explained within standard QM as differences in the effective operator set $\{Ai\}$.
The aim of the present framework is not empirical deviation but *conceptual internalization*:
to treat the measurable operator set as an endogenous component of the observer's structure and to formalize the consistency dynamics that accompany it.

6. Philosophical Implications — Observerhood and the Structural Turn

6.1 Consciousness and Observerhood

Observerhood is defined as an informational structure that enables the stabilization of consistency, without being reducible to consciousness.
The key question is not *who* observes, but *how* informational coherence emerges.
Consciousness can then be regarded as a special subclass of observerhood—one that exhibits higher-order self-referential organization and meta-consistency.
Thus, consciousness is not excluded but rather situated within a broader category of informationally coherent structures.
In this framework, an *observer* is not necessarily a subject of experience, but a structural entity that maintains informational stability.

6.2 Observerhood as Informational Structure

The consistency function $C(\rho, \phi)$ acts as a kind of *informational energy*, driving the update of observerhood along its gradient.
Observation is not the passive reception of information, but an active process of *self-consistent organization* within an informational geometry.
In this sense, reality is not merely mirrored by the observer; it is *stabilized* through the internal dynamics of informational coherence.

6.3 Consistency and the Fixation of Reality

"Reality" emerges as the stable point of alignment between the quantum state ρ and the observer's structure ϕ.
This fixation is not a physical collapse of the wave function, but a non-unitary stabilization of informational consistency.
Unlike Penrose's (1996) proposal of gravitationally induced collapse, the present model

does not postulate a new physical mechanism.
Instead, it reinterprets the stabilization of outcomes as the self-consistent alignment of informational structures.

6.4 Reframing the Question

The traditional question, "Why is this basis selected?" is replaced with a structural question: "Why does the observer experience this basis as consistent?"
Basis selection is no longer an event but an equilibrium of informational stability.
The measurement problem thus shifts from a *causal* to a *structural* mode of explanation.

6.5 Structural, Relational, and Informational Realisms

The proposed model of observerhood reformulates measurement as the *alignment between a quantum state and an observer's structure*.
Its metaphysical background belongs not to object-centered realism but to *structural realism*—the view that what persists through scientific change are not individual objects but structural relations (Worrall, 1989; Ladyman & Ross, 2007).
The functions $C(\rho, \phi)$ and ρ_ϕ formalize precisely this stability of relational structure.

Observerhood, in this sense, is not a single conscious entity but a *network of informational structures* that constitute the conditions of observability.
This places the theory in close dialogue with Rovelli's (1996) *Relational Quantum Mechanics* (RQM), which defines states only relative to other systems.
The consistency dynamics proposed here can be interpreted as a formalization—within information geometry—of the relational update process envisioned by RQM.

At the same time, Floridi's (2011) *Informational Structural Realism* (ISR) reconstructs structural realism from the philosophy of information, conceiving reality as *"a difference that makes a difference."*
Given that $C(\rho, \phi)$ measures precisely the informational difference between quantum state and observer structure,
the present framework can be viewed as a natural physical model of ISR.
By quantifying the stabilization of informational difference via information geometry, this approach provides a mathematical foundation for informational realism.

Taken together, the model of observerhood proposed here integrates
the ontic foundation of *Ontic Structural Realism (OSR)*,
the relational stance of *RQM*,
and the informational reformulation of *ISR*.
Observation becomes the process through which informational structures stabilize into coherence,
and reality is understood as the network of relations that maintain such coherence.

6.6 Toward an Integrated Principle of Consistency

The consistency function $C(\rho, \varphi)$ suggests a latent framework connecting three layers: **information (quantum state ρ)**, **meaning (observer structure ϕ)**, and **physics (measurement outcome)**.
Extending this idea, one may envision an *Integrated Consistency Principle* that unifies observation, prediction, and meaning-generation within a single theoretical scheme.

This direction resonates with Dennett's notion of *real patterns* (1991),
Whitehead's process philosophy of interrelated events (1929),
and Floridi's informational realism.
Information geometry could then serve as the mathematical framework that formalizes these structural and informational ideas, describing the co-emergence of observer and world as a mutually generative process.

While this paper does not develop that integrated framework in detail,
it points toward the construction of a *general structural theory* that interconnects the informational (I), meaningful (M), and physical (P) layers.
We may tentatively refer to this emerging scheme as the *M-meta-structure*.
Clarifying its mathematical formulation and its relation to existing physical theories remains an open task for future research.

7.Limitations & Future Work

7.1 Limitations and Future Work

The present theory does not explain the *origin* of basis selection in quantum measurement.
The set of measurable operators $\{Ai\}$ is determined by exogenous factors such as the environment, apparatus design, and learning history.
The proposed framework should therefore be understood as an *informational-geometric trial* describing how an observer achieves internal consistency with respect to a given basis, rather than as a theory that generates the basis itself.

7.2 Physical Meaning of the Informational Diffusion Coefficient *D*

The coefficient *D* represents the level of informational noise or *learning temperature* within the observer.
It can be interpreted as a ratio of time scales,

$$D \sim \frac{\tau_{\text{relax}}}{\tau_{\text{obs}}}$$

where smaller *D* corresponds to long-time, high-precision observation (high consistency), and larger *D* to short-time, low-precision observation (low consistency).
Thus *D* acts as an internal thermodynamic parameter governing the sharpness of structural stabilization.

7.3 Unresolved Issue of Discretization

The mechanism by which continuous consistency distributions yield discrete outcomes is not specified in this paper.
It is presumed to result from a combination of environmental coarse-graining, finite-time stabilization, and the finite-dimensional structure of measurement apparatuses.
A more detailed account of this discretization process remains an open question for future research.

7.4 Directions for Future Work

The future development of this theory can be organized along three complementary dimensions: **theoretical deepening**, **mathematical refinement**, and **empirical validation**.

- **Theoretical deepening:** Endogenize the measurable operator set $\{Ai\}$ and derive a generative model of observerhood ϕ.
- **Mathematical refinement:** Derive the informational diffusion coefficient D from statistical mechanics, integrating information geometry with non-equilibrium thermodynamics.
- **Empirical validation:** Analyze concentration phenomena through gradient-flow simulations of the consistency dynamics.
- **Extended applications:** Generalize the model to higher-dimensional systems (harmonic oscillators, quantum fields).
- **AI-based verification:** Implement conceptual experiments using artificial observers in machine-learning environments.

7.5 Conclusion

This study has reinterpreted quantum measurement as a *dual process* of **external decoherence** and **internal consistency**, repositioning the measurement problem as one of *structural coherence* rather than physical collapse.
The proposal does not claim to solve the measurement problem but to *reconstruct* it—providing a foundational bridge between quantum theory, information geometry, and the philosophy of science.

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