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An Operational Causal-Symmetry Framework for Quantum Nonlocality and Information

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Abstract

This paper studies a minimal time-symmetric operational framework in which information from initial preparation and post-selection is used to define an operational description of quantum evolution. Quantum randomness is interpreted as epistemic incompleteness rather than ontological indeterminacy. The central dynamical object is the informational coupling map $\Lambda_\kappa(\rho) = (1-\kappa)\rho + \kappa\sigma_Z$, which mixes the actual state ρ with a fixed reference state σ_Z. The channel itself is mathematically standard; the contribution of the manuscript is the operational interpretation of the dimensionless coupling parameter κ as a measure of boundary alignment, its entropy-based estimation under explicitly stated assumptions, and its embedding in a delayed-choice quantum random number generator (QRNG) protocol. A Gorini–Kossakowski–Sudarshan–Lindblad (GKSL) representation of the corresponding continuous-time dynamics is given using a separate relaxation rate γ, complete positivity is explicit, and no-signaling is preserved under the proposed local action. In the limit $\gamma \to 0$, standard unitary quantum mechanics is recovered, whereas nonzero γ produces small deviations that can be interpreted as effective informational bias associated with post-selection. In the present framework, σ_Z is not treated as a universal microscopic final state, but as a context-dependent operational reference state determined by the post-selection structure used in the model.

Keywords: quantum mechanics, quantum nonlocality, causal symmetry, quantum information, boundary conditions, informational thermodynamics

1. Introduction

Einstein's dictum that "God does not play dice" captures the long-standing tension between determinism and the apparent indeterminacy of quantum phenomena. Bell-type experiments have confirmed nonlocal correlations, yet they do not by themselves explain why individual outcomes appear random. In standard quantum mechanics, the initial state constrains forward evolution, whereas the final outcome is treated probabilistically by the Born rule. This temporal asymmetry motivates the following question: can part of the apparent randomness be modeled operationally as incomplete access to correlations connecting preparation and post-selection?

The aim of this paper is specific and limited. It does *not* claim a new mathematical class of quantum channels or a new general theory of boundary-value problems in mathematical physics. Instead, it uses a simple, well-known relaxation channel as a minimal operational framework for describing evolution conditioned on initial preparation and post-selection information. The novelty claimed here is therefore interpretive and operational: the manuscript associates the relaxation structure with a dimensionless boundary-alignment parameter κ, derives experimentally usable estimators for κ under explicit assumptions, and embeds the framework in a delayed-choice QRNG protocol.

Conceptually, the framework is related to the Two-State Vector Formalism (TSVF) (Aharonov, Bergmann, & Lebowitz, 1964; Aharonov, & Vaidman, 1991), the transactional interpretation (Cramer, 1986), relational quantum mechanics (Rovelli, 1996), QBism (Fuchs, Mermin, & Schack, 2014), and frameworks without fixed causal order (Oreshkov, Costa, & Brukner, 2012), but it differs in the following sense. Instead of introducing hidden variables or two independently evolving state vectors, the present paper treats preparation and post-selection as informational constraints on a single density operator and studies the simplest CPTP interpolation toward a fixed reference state σ_Z. In the present framework, σ_Z is not postulated as an ontic final state of nature. Rather, it is an operationally specified reference density operator determined by the chosen post-selection protocol or measurement context. Its role is therefore model-defining and contextual: different post-selection schemes may lead to different admissible choices of σ_Z. Here the subscript "Z" is only a label for the reference state; it does *not* denote the Pauli matrix σ_z.

2. Model Description

2.1 Operational Definition of the Alignment Parameter κ

Consider a quantum system $(\mathcal{H}, \rho_0, H, \{E_i\})$ with Hilbert space $\mathcal{H}$, initial density operator ρ_0, Hamiltonian H, and measurement operators E_i. We introduce a dimensionless parameter $\kappa \in [0, 1]$ that quantifies the effective alignment between pre-selection and post-selection at the level of operationally accessible statistics.

The primary definition used in this paper is the normalized mutual-information form

$$\kappa := \frac{I(\text{pre} : \text{post})}{I_{\max}}. \tag{1}$$

To make this precise operationally, let a and b denote classical labels for the coarse-grained pre-selection and post-selection outcomes. We define the joint state

$$\rho_{\text{joint}} := \sum_{a,b} p(a, b)\ |a\rangle\langle a| \otimes |b\rangle\langle b|, \tag{2}$$

with marginals

$$\rho_{\text{pre}} := \sum_{a} p(a)\, |a\rangle\langle a|, \qquad \rho_{\text{post}} := \sum_{b} p(b)\, |b\rangle\langle b|. \tag{3}$$

In this coarse-grained classical setting,

$$I(\text{pre} : \text{post}) = S(\rho_{\text{pre}}) + S(\rho_{\text{post}}) - S(\rho_{\text{joint}}), \tag{4}$$

where $S(\cdot)$ is the von Neumann entropy, which here reduces to the Shannon entropy of the corresponding classical distributions.

For a coarse-grained classical label space with d accessible outcomes and a uniform reference alphabet, we set

$$I_{\max} := \ln d. \tag{5}$$

Thus κ is a normalized, dimensionless alignment measure in the chosen coarse-grained setting.

To connect Eq. (1) with observable frequency data, we impose an additional measurement-level assumption: the relevant statistics are described by a d-outcome distribution $P_{\text{obs}} = \{p_i\}_{i=1}^{d}$ and are compared with the maximally uninformative baseline $u_i = 1/d$. We then define the observed Shannon entropy

$$S_{\text{obs}} := -\sum_{i=1}^{d} p_i \ln p_i \tag{6}$$

and the maximal accessible entropy

$$S_{\max} := \ln d. \tag{7}$$

Under this specific coarse-grained assumption,

$$I_{\text{eff}} := S_{\max} - S_{\text{obs}} = D_{\text{KL}}(P_{\text{obs}} \| u), \tag{8}$$

which leads to the operational estimator

$$\kappa_{\text{est}} := \frac{I_{\text{eff}}}{S_{\max}} = 1 - \frac{S_{\text{obs}}}{S_{\max}}. \tag{9}$$

Equation (9) is therefore *not* claimed as a general identity for arbitrary quantum states. It is only an operational estimator valid under the stated coarse-graining and baseline choice. Accordingly, κ is interpreted throughout this paper as an operational descriptor of boundary alignment at the level of accessible statistics, not as a uniquely derived microscopic constant of nature.

For thermodynamic bookkeeping we use the standard informational relation

$$\Delta I := -\frac{\Delta S_{\text{sys}}}{k_B}, \tag{10}$$

where ΔS_{sys} denotes the change in system entropy and k_B is Boltzmann's constant. In the present manuscript this serves only as an interpretive consistency relation in the Landauer–Jaynes spirit (Landauer, 1961; Jaynes, 1957; Jarzynski, 2011;

Deffner, & Jarzynski, 2013; Deffner, & Campbell, 2019); it is not required for the mathematical definition of the channel.

2.2 Quantum Channel and Continuous-Time Dynamics

The informational map is modeled by the CPTP channel

$$\Lambda_\kappa(\rho) = (1-\kappa)\rho + \kappa\sigma_Z, \qquad 0 \le \kappa \le 1, \tag{11}$$

where σ_Z is an operational reference state associated with the selected post-selection structure. More precisely, σ_Z is not introduced here as a uniquely specified microscopic final boundary condition. Rather, it is the effective density operator representing the retained post-selection context at the level of accessible statistics. Depending on the implementation, σ_Z may be specified as: (i) the density operator associated with a selected post-measurement basis state, (ii) the reconstructed state of the retained post-selected ensemble, or (iii) a full-rank coarse-grained reference state inferred from the asymptotic statistics of the post-selection protocol. In this sense, σ_Z is fixed by the experimental design and is not a freely tunable ontological parameter. For the GKSL construction below, σ_Z is assumed to be full rank. The map is mathematically standard and relaxes any input state toward a fixed target state.

2.3 Operational Admissibility and Selection of σ_Z

The reference state σ_Z must satisfy the standard requirements of a density operator,

$$\sigma_Z \ge 0, \qquad \mathrm{Tr}(\sigma_Z) = 1.$$

For the GKSL representation used below, we further assume that σ_Z is full rank, so that in the spectral decomposition

$$\sigma_Z = \sum_k p_k \left|k\right\rangle \left\langle k\right|,$$

all eigenvalues satisfy $p_k > 0$. When the thermodynamic interpretation of Section 3 is invoked, we additionally impose the stationarity condition

$$[H, \sigma_Z] = 0.$$

These assumptions should be understood as model conditions, not as claims that every post-selection protocol uniquely determines a single microscopic final state. The role of σ_Z in the present framework is operational: it is the reference density operator specified by the retained post-selection structure and used to parameterize the effective relaxation channel.

To define the corresponding local action on a bipartite system rigorously, let $\sigma_Z^{(B)}$ denote the reference state on subsystem B, and define the trace-preserving replacement map on operators X_B by

$$\Lambda_\kappa^{(B)}(X_B) := (1-\kappa)X_B + \kappa\, \mathrm{Tr}(X_B)\sigma_Z^{(B)}. \tag{12}$$

For a bipartite state ρ_{AB} with marginal $\rho_A = \mathrm{Tr}_B\,\rho_{AB}$, local action on subsystem B then gives

$$(I_A \otimes \Lambda_\kappa^{(B)})(\rho_{AB}) = (1-\kappa)\rho_{AB} + \kappa\,\rho_A \otimes \sigma_Z^{(B)}. \tag{13}$$

Tracing out B yields

$$\mathrm{Tr}_B[(I_A \otimes \Lambda_\kappa^{(B)})(\rho_{AB})] = \rho_A, \tag{14}$$

so the local marginal on subsystem A remains unchanged. Hence the proposed local action preserves no-signaling.

To avoid a dimensional inconsistency, the continuous-time dynamics is written with a separate relaxation rate $\gamma \ge 0$ of dimension 1/time. Including the standard unitary term generated by H, we obtain

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] - \gamma(\rho - \sigma_Z). \tag{15}$$

This equation describes competition between Hamiltonian evolution and exponential relaxation toward the reference state. The dimensionless quantity κ characterizes operational alignment; the parameter γ sets the physical time scale of relaxation.

In the present paper, the discrete map Λ_κ and the continuous-time GKSL dynamics generated by γ are used as complementary operational parameterizations of the same boundary-alignment idea, without claiming a unique microscopic identification between κ and γ.

Let

$$\sigma_Z = \sum_k p_k \, |k\rangle \langle k| , \qquad p_k > 0, \tag{16}$$

and define jump operators

$$L_{kj} = \sqrt{\gamma p_k} \, |k\rangle \langle j| . \tag{17}$$

Then the generator can be written in GKSL form as

$$\mathcal{L}(\rho) = -\frac{i}{\hbar}[H, \rho] + \sum_{k,j} \left(L_{kj} \rho L_{kj}^\dagger - \frac{1}{2} \{ L_{kj}^\dagger L_{kj}, \rho \} \right). \tag{18}$$

Using $\sum_{k,j} L_{kj}^\dagger L_{kj} = \gamma I$, one verifies that Eq. (18) reproduces Eq. (15). Therefore $e^{t\mathcal{L}}$ is a CPTP semigroup.

3. Thermodynamic Interpretation

This section does not provide an independent thermodynamic derivation of the channel. Its more limited purpose is to show that the proposed relaxation dynamics is compatible with standard information-theoretic and CPTP-contractivity considerations when σ_Z is treated as a stationary reference state.

The channel itself is standard, but it admits a simple informational reading. Define the internal energy

$$U = \mathrm{Tr}(\rho H), \tag{19}$$

the von Neumann entropy

$$S(\rho) = -\mathrm{Tr}(\rho \ln \rho), \tag{20}$$

and the informational free energy

$$F_{\mathrm{info}} := U - k_B T S(\rho). \tag{21}$$

We also define the quantum relative entropy with respect to the reference state

$$D(\rho \| \sigma_Z) := \mathrm{Tr}[\rho(\ln \rho - \ln \sigma_Z)]. \tag{22}$$

When σ_Z is stationary under the Hamiltonian part, i.e. $[H, \sigma_Z] = 0$, the dissipative term in Eq. (15) drives relaxation toward σ_Z. For GKSL semigroups with stationary reference state, monotonic decrease of relative entropy is a standard contractivity property under CPTP evolution, so it is natural here to use

$$\frac{d}{dt} D(\rho_t \| \sigma_Z) \leq 0 \tag{23}$$

as the core thermodynamic consistency condition associated with the relaxation term. This monotonicity is invoked here as a standard contractivity property of CPTP semigroups with stationary reference state. In the present manuscript it is used as a standard property rather than as a newly derived theorem.

Likewise, the free-energy interpretation is used only qualitatively. Under the same stationarity assumption, relaxation toward σ_Z is consistent with a non-increasing informational free-energy picture, but no exact balance law is claimed here. No stronger equality for $\dot{Q}_{\mathrm{info}}$ or dF_{info}/dt is required for the present argument.

4. Experimental Validation: Delayed-Choice QRNG

A delayed-choice QRNG provides a simple operational setting in which an experimental estimator of the alignment quantity may be extracted from measured statistics. Single photons (wavelength $\lambda \sim 810\,\mathrm{nm}$, pulse width $\sim 10\,\mathrm{ns}$) pass through a 45° polarizing beam splitter and are detected at (D_H, D_V). The basis choice is implemented by an electro-optic modulator and accessed only after detection. In this operational setting, σ_Z is identified with the effective reference density operator associated with the selected measurement basis and the retained post-selected ensemble. In the simplest implementation, if a single post-selected basis outcome is retained, σ_Z may be taken as the corresponding pure-state projector. If a full-rank state is required for the semigroup formulation or if the retained ensemble is coarse-grained, σ_Z is replaced by the corresponding full-rank effective density operator. Thus σ_Z is fixed by the experimental protocol before parameter estimation is performed.

At the level of experimentally fitted outcome probabilities, we introduce the following first-order phenomenological parameterization of a possible post-selection bias:

$$P_H = \frac{1}{2}(1 + \kappa\,\delta_H), \qquad P_V = \frac{1}{2}(1 - \kappa\,\delta_H), \tag{24}$$

where δ_H is a calibration factor accounting for residual detector asymmetry. This is not presented as a unique microscopic derivation from the channel, but as a leading-order phenomenological ansatz used to estimate a small alignment effect under the stated experimental assumptions.

The corresponding fit-based estimator is

$$\kappa_{\rm fit} = \frac{2(P_H - P_V)}{\delta_H}. \tag{25}$$

Within the proposed framework, $\kappa_{\rm fit}$ is interpreted as an experimental estimator of the same operational alignment quantity denoted abstractly by κ, while $\kappa_{\rm est}$ in Eq. (9) is the entropy-based estimator built from the observed outcome distribution. With detection efficiency $\eta \approx 0.9$ and sample size $n \geq 10^6$, the statistical uncertainty is approximated by

$$\sigma_\kappa = \frac{2}{\delta_H}\sqrt{\frac{P_H(1 - P_H)}{n}}, \tag{26}$$

which places the relevant sensitivity regime near $\kappa \approx 10^{-2}$ for realistic parameters.

5. Comparative Summary of Interpretations

Table 1 summarizes the main structural differences between the present operational framework and several widely discussed interpretations.

Table 1. Comparative summary of interpretations

Interpretation	Temporal Symmetry	Dynamics	Info Coupling	Empirical Testability
Copenhagen	No	Stochastic collapse	None	Indirect
TSVF	Yes	Kinematic	Implicit	Weak values
Transactional	Yes	Offer–confirmation	Qualitative	Conceptual
Relational/QBism	Yes (rel.)	None	Subjective	Indirect
Causal symmetry	**Yes**	**Unitary + CPTP semigroup**	**κ (operational)**	**Proposed direct test (QRNG)**

6. Conclusion

The present manuscript does not introduce a new class of quantum channels, nor does it claim that σ_Z is a universal microscopic final state. Its contribution is narrower: it interprets a standard relaxation channel as a minimal operational framework for temporal boundary alignment, defines a dimensionless operational coupling parameter κ, clarifies the assumptions under which entropy-based estimation is valid, separates κ from the dynamical relaxation rate γ, and embeds the framework in a concrete delayed-choice QRNG test scenario. Within this framework, σ_Z is a context-dependent operational reference state fixed by the post-selection protocol and used to parameterize the effective relaxation structure. Within this formulation, apparent randomness is treated as epistemic rather than ontological, while no-signaling and complete positivity are preserved.

The QRNG component is presented as an operational test proposal for an alignment parameter, not as a unique microscopic prediction that by itself excludes all ordinary open-system or calibration effects. Any eventual empirical claim would therefore require careful control experiments and comparison against standard noise models.

6.1 Future Work

Future work should focus on three points: first, deriving tighter relations between the operational estimators $\kappa_{\rm est}$ and $\kappa_{\rm fit}$ and the physical relaxation rate γ; second, extending the construction to multipartite and field-theoretic settings; and third, identifying whether any measured deviations can genuinely discriminate this boundary-alignment picture from ordinary calibration drift or known open-system effects.

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Competing Interests

The author declares no conflict of interest.

Author Contributions

The author conceived the study, developed the causal-symmetry operational framework, carried out the analytical derivations, and wrote and revised the manuscript.

Data Availability

Data sharing does not apply to this article as no datasets were generated or analyzed during the current study. All derivations and results are contained in this manuscript.

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Appendix A: Mathematical Details

A.1 Trace Preservation

From Eq. (11),

$$\mathrm{Tr}[\Lambda_\kappa(\rho)] = (1-\kappa)\mathrm{Tr}(\rho) + \kappa\mathrm{Tr}(\sigma_Z) = 1.$$

A.2 Admissibility Conditions on the Reference State

The reference operator σ_Z must satisfy the defining properties of a density operator,

$$\sigma_Z \geq 0, \qquad \mathrm{Tr}(\sigma_Z) = 1.$$

For the GKSL representation in Eq. (18), we further assume that σ_Z is full rank, so that its spectral decomposition

$$\sigma_Z = \sum_k p_k \left|k\right\rangle \left\langle k\right|$$

has strictly positive eigenvalues $p_k > 0$. If the thermodynamic interpretation of Section 3 is invoked, the additional stationarity condition

$$[H, \sigma_Z] = 0$$

is imposed. These conditions are sufficient for the operational and semigroup constructions used in the manuscript.

A.3 Complete Positivity

For the local channel defined in Eq. (12), the Choi operator is

$$J(\Lambda_\kappa^{(B)}) = (I \otimes \Lambda_\kappa^{(B)})(|\Phi\rangle \langle\Phi|),$$

where $|\Phi\rangle$ denotes a maximally entangled state on the doubled Hilbert space. Explicitly,

$$J(\Lambda_\kappa^{(B)}) = (1-\kappa)\,|\Phi\rangle\langle\Phi| + \kappa \frac{I \otimes \sigma_Z^{(B)}}{d},$$

which is positive for $0 \le \kappa \le 1$ because it is a convex combination of positive operators.

A.4 Exponential Convergence

Let $\delta\rho = \rho - \sigma_Z$. If $[H, \sigma_Z] = 0$, then Eq. (15) implies

$$\dot{\delta\rho} = -\frac{i}{\hbar}[H, \delta\rho] - \gamma\,\delta\rho,$$

so the dissipative contribution contracts exponentially with characteristic relaxation time

$$\tau = \frac{1}{\gamma}.$$

A.5 Numerical Example

For $\rho(0) = \frac{1}{2}(I + \sigma_x)$, $\sigma_Z = \frac{1}{2}(I + \sigma_z)$, and $\gamma = 0.05$ (with $H = 0$ for simplicity),

$$\rho(t) = \frac{1}{2}\left[I + e^{-\gamma t}\sigma_x + (1 - e^{-\gamma t})\sigma_z\right],$$

which illustrates Bloch-vector relaxation toward the reference state.

Abbreviations

CPTP	Completely Positive Trace-Preserving
GKSL	Gorini–Kossakowski–Sudarshan–Lindblad
QRNG	Quantum Random Number Generator
TSVF	Two-State Vector Formalism
QBism	Quantum Bayesianism