Records and Responses

Dressing-blind theorems for monitored quantum instruments

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4 July 2026

Abstract

We isolate a class of monitored quantum systems—*latched instruments*—in which every observable splits exactly into a *record* class, diagonal in a fixed dynamically absorbing pointer decomposition, and a *response* class carrying all off-diagonal support. Five elementary but useful theorems follow. (T1) Record statistics form a single classical probability space; coincidence rates for independent preparations factorise at diagonal Born weights, and every retarded correlator built from records vanishes identically. (T2) Pointer-conditional dressing leaves the entire record algebra invariant as an operator identity while renormalising response observables by Franck–Condon overlaps: the same interaction cloud leaves bills fixed while changing responses. (T3) The record channel's pole residue is exactly 1—the LSZ residue of a record cannot be renormalised—while a bare response excitation carries residue $Z < 1$ with the deficit exactly in the dressing continuum. (T4) Latched accumulation is a functional of the source alone, independent of any washout profile applied to unlatched components; each event is billed once. (T5) The additive contact to which fluctuation–dissipation and Kramers–Kronig reconstructions are provably blind is fixed by the Euclidean zero-frequency value: local subtraction constants belong to the record side of the split. Each theorem is certified by a short self-checking program distributed with the paper. We state explicitly which parts are standard material made exact and which readings are new in this presentation, and sketch applications to measurement statistics, quantum-Darwinism redundancy, spectator-charge accumulation, and normal-ordering constants in dressed couplings.

1 Introduction

Two kinds of question are asked of a quantum system, and they are not symmetric. One kind asks *what has been written down*: which detector fired, which flux value latched, what a memory holds. The other asks *how the system leans*: susceptibilities, amplitudes, interference visibilities, dressed energies. The standard formalism treats both as "observables," and much of the folklore of measurement theory is obscured by that compression.

This paper develops the asymmetry as a set of exact, finite-dimensional theorems. We fix a class of monitored systems—*latched instruments* (Definition 1)—in which a preferred orthogonal decomposition of the system is dynamically absorbing: once the state has committed to a sector, subsequent dynamics acts within sectors. Such structure is not introduced ad hoc; it is the generic endpoint of einselection, the environment superselecting a pointer basis and proliferating copies of the outcome [1–3]. What we add is not a mechanism but a ledger: given the structure, the observable algebra splits into a commutative *record* algebra and its off-diagonal complement, the *response* class, and the split supports five sharp statements.

T1 *Diagonal billing.* Record statistics are those of a single classical probability space; joint records of independently prepared systems factorise at diagonal Born weights; and all retarded (commutator) correlation functions built from records vanish identically. Records are conserved charges of the latched era.

T2 *Dressing-blindness.* Every pointer-conditional dressing—an arbitrary environment unitary conditioned on the pointer sector—leaves every record observable invariant as an operator identity, while renormalising response observables by Franck–Condon overlap factors. The same cloud that drags a response cannot touch a bill.

T3 *Unit spectral weight.* In the dressed eigenstructure, the record operator connects dressed states with pole residue exactly 1 and zero leakage into the continuum, whereas a bare response excitation has residue $|Z| < 1$ with the deficit exactly in the orthogonal complement. Wave-function renormalisation is confined to the response class.

T4 *The latch.* With absorbing sector dynamics, each record event is billed exactly once, and the accumulated record is a functional of the source history alone—exactly independent of any washout profile acting on unlatched components.

T5 *The Euclidean bridge.* A real additive contact in a retarded kernel is invisible to the dissipative data—fluctuation–dissipation and Kramers–Kronig reconstructions determine the kernel only modulo the contact—yet it survives, exactly, in the Euclidean zero-frequency value. Subtraction constants are record-side quantities.

The proofs are elementary, and we do not claim otherwise; Section 8 states precisely which ingredients are folklore and where the sharpening lies. The claim is that the *package* is useful: the five statements are the exact skeleton underneath a number of arguments that are usually run heuristically — why detector counts carry no factor of Z while amplitudes do, why decoherence-era statistics obey a classical calculus, why spectator charges survive washout model-dependence, and why a normal-ordering constant that no response measurement can see is nevertheless fixed by a Euclidean computation. Each theorem is certified by an executable program (Appendix A); every numerical claim in the text is an output of that program.

Throughout, all Hilbert spaces are finite-dimensional. This is a deliberate restriction: it keeps every statement checkable by elementary linear algebra, and it matches the operational situation — any actual record is finite.

2 The instrument class

Definition 1 (Latched instrument)**.** *A* latched instrument *is a triple* $(\mathcal{H}_S \otimes \mathcal{H}_E,\ \{\Pi_r\}_{r\in R},\ \mathcal{V})$ *where* $\{\Pi_r\}$ *is a family of orthogonal projections on* $\mathcal{H}_S$ *with* $\sum_r \Pi_r = \mathbb{1}_S$ *(the* pointer decomposition*), and* $\mathcal{V}$ *is a set of admissible evolutions, each of the* pointer-conditional *form*

$$V \;=\; \sum_r \Pi_r \otimes U_r, \qquad U_r \text{ unitary on } \mathcal{H}_E. \tag{1}$$

The record algebra $\mathcal{R}$ *is the commutative algebra generated by* $\{\Pi_r \otimes \mathbb{1}_E\}$*. Observables in* $\mathcal{R}$ *are* records*; observables with non-zero off-diagonal blocks* $\Pi_r X \Pi_s$*,* $r \neq s$*, are* responses*.*

Equation (1) is the statement that the pointer decomposition is *absorbing* during the monitored era: dynamics may build arbitrary environment clouds, differently in each sector, but does not transfer weight between sectors. We call any such V a *dressing* or *cloud.* The class is exactly the measurement-limit structure familiar from von Neumann's chain [4] and from the pointer-basis literature [1]; in open-system language it is the commutant structure of a quantum non-demolition coupling [5, 6]. Which decomposition latches, and how fast, is einselection's business, settled by the system–environment coupling; we take the decomposition as given and prove consequences.

Two conventions. First, “billing”: a state ρ *bills* sector r the weight $p_r = \mathrm{Tr}[(\Pi_r \otimes \mathbb{1})\rho]$; the theorems below are about what can and cannot alter bills. Second, all statements quantified over “every cloud” mean every V of the form (1), with no restriction on the U_r.

3 T1: diagonal billing

Theorem 1 (Diagonal billing)**.** *Let A and B be systems with pointer decompositions $\{\Pi_a\}$, $\{\Sigma_b\}$ in a joint latched instrument. Then:*

(i) For any joint state ρ, the numbers $p(a,b) = \mathrm{Tr}[(\Pi_a \otimes \Sigma_b)\,\rho]$ form a single classical probability distribution, and all record observables possess a joint spectral measure: record statistics admit a non-contextual classical description.

(ii) If $\rho = \rho_A \otimes \rho_B$, coincidence rates factorise at the diagonal Born weights: $p(a,b) = p(a)\,p(b)$ with $p(a) = \mathrm{Tr}[\Pi_a \rho_A]$.

(iii) Records are pointwise fixed by every cloud, $V^\dagger(R)\,V = R$ for all $R \in \mathcal{R}$; hence records are conserved charges of the latched era, and every retarded correlator of records, $G^{\mathrm{ret}}_{R_1 R_2}(t) \propto \theta(t)\ \mathrm{Tr}(\rho\,[R_1(t), R_2(0)])$, vanishes identically.

Proof. (i) The generators $\Pi_a \otimes \mathbb{1}$, $\mathbb{1} \otimes \Sigma_b$ commute, so $\mathcal{R}_A \vee \mathcal{R}_B$ is commutative; a commutative $*$-algebra of observables is $*$-isomorphic to functions on its joint spectrum, and ρ restricts to a classical measure on that spectrum. Positivity and normalisation of $p(a,b)$ are immediate. (ii) follows by factorising the trace. (iii) With V as in (1), $V^\dagger(\Pi_r \otimes \mathbb{1})V = \Pi_r \otimes U_r^\dagger U_r = \Pi_r \otimes \mathbb{1}$; linearity and multiplicativity extend this to all of $\mathcal{R}$. Records at all times coincide, so all commutators at unequal times reduce to equal-time commutators within a commutative algebra, which vanish. □

Remark 1. Clause (i) is deliberately scoped: it asserts classicality of the statistics of *one fixed* latched decomposition per system. The setting-dependence probed by Bell tests lives in the choice of *which* decomposition latches (a different measurement latches a different one) and is untouched by the theorem. Within a run, the records form one sample space; across incompatible settings, no joint space is claimed.

The certified demonstration prepares a product of two qubit states with non-trivial coherences and verifies $p(1,1)$ equals the product of diagonal weights to 10^{-15}, and that the record–record commutator is the zero matrix exactly.

4 T2: dressing-blindness

Theorem 2 (Dressing-blindness)**.** *Let $V = \sum_r \Pi_r \otimes U_r$ be any cloud. Then:*

*(i) (*Records*) $V^\dagger R\, V = R$ for every $R \in \mathcal{R}$; record statistics of every state are exactly invariant.*

*(ii) (*Responses*) Let $X = (|s\rangle\langle r| + |r\rangle\langle s|) \otimes \mathbb{1}_E$ be a bare coherence operator between sectors $r \neq s$, with $|r\rangle, |s\rangle$ unit vectors in their sectors, and let the environment be prepared in $|\phi\rangle$. Matrix elements dress by the Franck–Condon overlap:*

$$\langle V(\psi \otimes \phi)|\, X\, |V(\psi' \otimes \phi)\rangle \;=\; \langle U_s\phi|U_r\phi\rangle\, \langle\psi|s\rangle\langle r|\psi'\rangle \;+\; \langle U_r\phi|U_s\phi\rangle\, \langle\psi|r\rangle\langle s|\psi'\rangle, \qquad (2)$$

so coherence expectations renormalise by $Z_{rs}^{1/2} = \langle U_s\phi|U_r\phi\rangle$ while every bill is fixed.

Proof. (i) is Theorem 1(iii). (ii) Insert $V(|r\rangle \otimes |\phi\rangle) = |r\rangle \otimes U_r|\phi\rangle$ and contract; the environment factor is $\langle U_s\phi|U_r\phi\rangle$. □

The force of the theorem is that (i) and (ii) hold for the *same* V. In the certified demonstration a single one-parameter cloud family leaves the record weight invariant to 10^{-15} while renormalising the coherence expectation from 1.00 to 0.17 of its bare value. This is the polaron/spin–boson renormalisation [7] viewed from the other side of the split: the familiar statement is that clouds dress coherences; the exact statement worth having is that the *record algebra is a fixed point of every cloud.*

5 T3: unit spectral weight

In scattering theory the residue of the single-particle pole—the wave-function renormalisation $Z \leq 1$ of the Källén–Lehmann representation [8, 9]—measures how much of a bare excitation survives dressing, and LSZ reduction divides it out of amplitudes [10]. The instrument split assigns Z a location: it lives entirely in the response class.

Theorem 3 (Unit residue of the record channel)**.** *Fix a cloud V, environment state $|\phi\rangle$, sector states $|r\rangle$, and write $|\Psi_r\rangle = V(|r\rangle \otimes |\phi\rangle)$ for the dressed sector states, $|\Psi\rangle = V\big(\sum_r c_r|r\rangle \otimes \phi\big)$ for a dressed superposition. Then:*

(i) $(\Pi_r \otimes \mathbb{1})\,|\Psi\rangle = c_r\,|\Psi_r\rangle$ *exactly: the record projection maps the dressed state onto the dressed sector state with the full Born amplitude. The record channel's pole residue is exactly* 1*, with zero leakage into any continuum.*

(ii) A bare inter-sector excitation $X_{sr} = |s\rangle\langle r| \otimes \mathbb{1}$ *applied to* $|\Psi_r\rangle$ *has overlap* $\langle \Psi_s|X_{sr}|\Psi_r\rangle = \langle U_s\phi|U_r\phi\rangle = Z_{sr}^{1/2}$ *with the dressed target; its pole residue is* $|Z_{sr}| \leq 1$*, and the missing weight* $1 - |Z_{sr}|$ *lies exactly in the orthogonal complement of the dressed sector state—the continuum's finite-dimensional stand-in.*

Proof. (i) $(\Pi_r \otimes \mathbb{1})V = V(\Pi_r \otimes \mathbb{1})$ by block diagonality, and $(\Pi_r \otimes \mathbb{1})$ applied to the undressed superposition gives $c_r|r\rangle \otimes |\phi\rangle$. Apply V. (ii) $X_{sr}|\Psi_r\rangle = |s\rangle \otimes U_r|\phi\rangle$; decompose $U_r|\phi\rangle = \langle U_s\phi|U_r\phi\rangle\, U_s|\phi\rangle + |\chi^{\perp}\rangle$ with $\langle U_s\phi|\chi^{\perp}\rangle = 0$; the first term is the dressed target, the second is orthogonal to it. □

Corollary 1. *No dressing, however strong, transfers record weight into a continuum; renormalisation constants* $Z < 1$ *attach exclusively to response operators. In field theory language: LSZ divides* Z *out of amplitudes, but a detector count never contained it.*

The certified demonstration extracts both residues from the same cloud family: the record residue is 1 to 10^{-15} at every coupling, while the bare response residue tracks $\cos^2\lambda < 1$ with the deficit landing, exactly, in the orthogonal complement.

6 T4: the latch

Records must not only resist dressing; they must resist being *unwritten.* We model the sector dynamics of an episode as an absorbing chain: admissible evolutions may move weight from *unlatched* sectors to *latched* (record) sectors, and act arbitrarily within sectors, but latched sectors are absorbing.

Theorem 4 (One-episode billing and washout gauge)**.** *(i) (*One episode, one bill.*) Along any branch of an absorbing sector chain, the indicator of a latched sector jumps from* 0 *to* 1 *at most once and never returns; the expected bill of sector* r *equals its absorption probability. No event is billed twice.*

(ii) (Washout profile-independence.) *Let a scalar accumulation obey* $\dot{Y} = S(z) - W(z)\, Y_{\text{unlatched}}$*, where the washout* $W \geq 0$ *acts only on unlatched weight and the source* S *deposits into the latched component. Then the terminal latched accumulation is*

$$Y_{\text{latched}}(\infty) \;=\; \int S_{\text{latch}}(z)\, dz, \tag{3}$$

identically for every *bounded measurable washout profile* W*. Washout history is a gauge degree of freedom of the latched ledger.*

Proof. (i) is the absorbing-Markov property: the latched indicator process is monotone along branches, so its increments form a $\{0,1\}$ jump occurring at most once; taking expectations gives the absorption probability. (ii) The latched component is decoupled from W by hypothesis; integrate. □

The content is in clause (ii)'s quantifier. In accumulation problems — a spectator charge deposited during an era of strong washout, a detector tally in a noisy environment — the model-dependence usually enters through $W(z)$, which is rarely known. If (and only if) the deposited quantity is latched, that entire model-dependence cancels exactly. The certified demonstration integrates the same source against three adversarial washout profiles (none, a step, a large oscillation): the latched terminal values agree to 10^{-12} while the unlatched control varies by more than a factor of 50.

7 T5: the Euclidean bridge

The final theorem locates a familiar ambiguity. Response kernels are reconstructed from dissipative data via the fluctuation–dissipation theorem [11, 12] and Kramers–Kronig relations; both see only the spectral (imaginary, odd) content. A *contact*—a real additive constant in frequency, a δ-function in time, the fingerprint of normal-ordering and short-distance subtractions—has no spectral content at all.

Theorem 5 (Contact assignment)**.** *Let a retarded kernel have the spectral representation*

$$K_R(\omega) \;=\; \int_{\nu_{\text{gap}}}^{\infty} d\nu\, \rho(\nu)\, \frac{2\nu}{\nu^2 - (\omega + i0)^2} \;+\; c, \qquad \rho \geq 0, \quad \nu_{\text{gap}} > 0, \quad c \in \mathbb{R}. \tag{4}$$

Then:

(i) $\operatorname{Im} K_R(\omega)$*, the FDT noise kernel at any temperature, and every Kramers–Kronig reconstruction from dissipative data are independent of* c*: no real-time response or noise measurement determines the contact.*

(ii) The Euclidean correlator $G_E(\tau) = \int d\nu\, \rho(\nu)\, e^{-\nu|\tau|} + c\,\delta(\tau)$ *retains it: the zero-frequency Euclidean value is* $\widetilde{G}_E(0) = \int d\nu\, \rho(\nu)\, \frac{2}{\nu} + c$*, and*

$$c \;=\; \widetilde{G}_E(0) \;-\; \mathrm{KK}[\operatorname{Im} K_R]\,(0) \tag{5}$$

is exactly recoverable from the Euclidean side.

Proof. (i) c is real and ω-independent, so it cancels from $\operatorname{Im} K_R$; FDT expresses noise through $\operatorname{Im} K_R$ alone, and unsubtracted KK integrals rebuild only the dispersive part. (ii) Integrate G_E over $\tau \in (-\infty, \infty)$; the spectral term gives $\int \rho\, 2/\nu$, the contact integrates to c. The gap makes both integrals absolutely convergent. □

This is, of course, the standard subtraction-constant ambiguity of dispersion relations. What the instrument split adds is an *assignment*: the dissipative data are response-class quantities, while the Euclidean/KMS correlator is computed in the thermal (record-side) state whose reconstruction theorems [13] carry the local terms. Constants that responses cannot see are not therefore ambiguous; they are fixed on the other side of the ledger. The certified demonstration hides a contact $c = 0.37$ in a gapped kernel, verifies the KK route returns the dispersion value alone, and recovers c from the Euclidean zero-frequency value to 10^{-9}.

8 Provenance: what is folklore, what is sharpened

Refereeing such statements fairly requires knowing where each came from. Table 1 gives the honest ledger.

	Established ancestry	**Sharpened here**
T1	Commutative record structures: operational QM [14, 15], decoherent histories [16], einselection [1].	Records as *pointwise-fixed* charges of the latched era; the identically-zero retarded record correlator as the *defining* boundary of the split.
T2	Franck–Condon / polaron / spin–boson renormalisation of coherences [7].	Exact invariance of the whole record algebra under *every* pointer-conditional cloud, as an operator identity; one cloud, two fates, certified numerically.
T3	Källén–Lehmann weight, $Z \leq 1$, LSZ reduction [8–10].	The complementary exact statement $Z_{\text{record}} = 1$ with zero continuum leakage; renormalisation *confined* to the response class.
T4	Absorbing Markov chains; quantum-jump trajectories [5, 6].	Washout history as an exact gauge freedom of latched accumulation (profile-independence with an adversarial certificate).
T5	Subtraction constants in dispersion relations; FDT [11, 12]; Euclidean reconstruction [13].	The *assignment* of the undetermined constant to the record side: FDT-blind, Euclidean-fixed, as an instrument dichotomy rather than a calculational nuisance.

Table 1: Provenance ledger for the five theorems.

Nothing in the mathematics above is difficult, and several clauses will be recognised, in other clothing, by specialists in each neighbouring literature. The contribution we claim is the split itself, taken seriously as an exact structure: five statements that are usually deployed heuristically and separately, here proved jointly from one two-line definition, with machine-checkable certificates.

9 Applications and outlook

Measurement statistics as billing. Within a latched decomposition, the reduction of outcome statistics to a single classical billing calculus is a *theorem* (T1), not an added rule. What remains genuinely dynamical is which decomposition latches, and that question belongs to einselection and Quantum Darwinism [1–3]. The split cleanly separates the solved from the open: billing calculus (here, exact) versus basis selection (there, physical). Flash-type ontologies [17–19], which populate the world with sparse definite events, sit naturally on the record side of the ledger.

Objectivity and broadcast. Records commute (T1), are cloud-invariant (T2), and carry unit residue (T3); they are therefore copyable without disturbance and survive arbitrary sectorconditional interaction with further environments. That is the operator-algebraic core of redundancy-based objectivity: what many observers can agree on is exactly what lives in $\mathcal{R}$.

Accumulation physics. Any conserved tally deposited into a latched channel—a spectator charge written during an early cosmological era, a dosimeter, an event counter—inherits T4's gauge property: the terminal ledger depends on the source history only, with all washout model-dependence cancelling exactly. In baryogenesis language, the discipline is to identify which charges are latched before arguing about washout at all.

Dressed couplings and normal-ordering constants. T5 is a practical instruction: when a coupling's local (contact) part is underdetermined by real-time response data, compute it Euclideanly; the two sides of the split cannot disagree, because only one of them carries the constant.

Relation to a companion programme. These theorems were distilled as instruments for a substrate research programme that models physical law as the bookkeeping of a finite error-corrected record [20–22]. Nothing in the present paper depends on that programme; the theorems are self-contained quantum-instrument statements, and readers who want only the instrument theory need read no further than Section 8.

A The certification program

A single self-checking script, `records_responses_instrument_theorems.py` (NumPy only), accompanies the paper. It exits with status 0 if and only if all checks pass; every numerical claim quoted in the text is one of its assertions:

- T1 a product of qubit states with coherences: the recorded coincidence rate equals the product of diagonal Born weights to 10^{-15}; the record–record commutator is the zero matrix exactly.
- T2 a one-parameter pointer-conditional cloud family: record weight invariant to 10^{-15} at every coupling; the coherence expectation renormalises from 1.00 to 0.17 under the same clouds.
- T3 dressed-state residues extracted from the same family: the record channel's residue equals 1 to 10^{-15} with continuum leakage below 10^{-30}; the bare response residue equals $\cos^2\lambda$ to 10^{-15}, strictly below 1.
- T4 one source, three adversarial washout profiles (none / step / large oscillation): latched terminal values agree within 10^{-12}; the unlatched control spans more than a factor of 50.
- T5 a gapped Lorentzian kernel with hidden contact $c = 0.37$: the Euclidean zero-frequency route minus the Kramers–Kronig route returns c to 10^{-9}; $\mathrm{Im}\, K_R$ is contact-independent identically.

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