

Beable Theory for Electron Spin Measurement: Pointer Localization, Spinor-Bundle Ontology, and Testable Record Statistics

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Abstract

We propose a phenomenological, testable objective-collapse framework—the Beable Theory—for electron spin measurements. An electron excitation carries a real internal orientation (a 'beable' field on the spinor bundle $S^3 \rightarrow S^2$) that generates coherent spinor precession, while stochastic collapse localizes a physically instantiated pointer variable encoding measurement records or environmental imprinting. Spin-state definiteness emerges when the spin entangles with distinct pointer configurations, enforcing single-run outcome selection via pointer localization, with ensemble dynamics reducing to pure dephasing in the measurement basis. We derive the reduced spin master equation, identifying the measurement-induced dephasing rate κ_{meas} with pointer-branch separation and parameterizing an always-on background channel κ_{bg} . Using published trapped-electron spectroscopy data (Fan et al., Phys. Rev. Lett. 130, 071801 (2023)), we translate the anomaly linewidth budget into an upper bound $\kappa_{\text{bg}} \lesssim 5 \times 10^{-2} \text{ s}^{-1}$ (order-of-magnitude), with a conservative bound $\kappa_{\text{bg}} \lesssim 2 \times 10^{-1} \text{ s}^{-1}$ from the full linewidth. The functional scaling in the strong-measurement (quantum Zeno) regime of circuit QED (Slichter et al., New J. Phys. 18, 053031 (2016)) is consistent with the model's dephasing structure. We provide a microscopic derivation of pointer-record noise statistics using continuous-measurement theory, establishing the Born rule via the martingale property of branch weights under diffusive unraveling. The beable modulates the effective measurement axis $\hat{a}_{\text{eff}}(t)$ in a gauge-invariant way depending only on the Bloch vector $\vec{r}(t)$, yielding testable signatures in trajectory-level pointer-record observables (e.g., variance, dwell times). Compatibility with Diósi–Penrose-type gravitational collapse is discussed, identifying κ_{bg} with a gravity-related rate $\kappa_{\text{DP}} \sim \Delta E_G / \hbar$ acting on pointer branches, suppressing macroscopic superpositions while preserving isolated spin coherence. A unified stochastic model and simulation program are outlined for bounding the basis-modulation parameter ε using public data.

Keywords: quantum measurement; objective collapse; pointer states; spin superposition; Penning trap; quantum Zeno effect; Diósi–Penrose model; spinor bundle; continuous measurement

1. Introduction

Quantum superposition is routinely verified at microscopic scales, yet measurement outcomes are definite. Standard quantum theory resolves this tension operationally via the Born rule and state-update postulates, but does not single out which physical degrees of freedom constitute the 'record' that becomes classical. Objective-collapse approaches postulate additional dynamics that suppress macroscopic superpositions. Motivated by an intuitive picture of an internal oscillation that is 'cut' at collapse, we develop a model in which (i) coherent evolution is generated by a real internal orientation carried by the electron excitation, and (ii) collapse is a stochastic localization of a physically instantiated pointer variable. The spin outcome is selected when the pointer becomes definite, not by a primitive collapse on the spin itself.

This Beable Theory supplements standard quantum mechanics with an ontological beable (internal orientation on the spinor bundle) and a pointer-localized collapse channel, ensuring emergent definiteness while preserving tested predictions. We emphasize testability through linewidth budgets, record statistics, and Zeno scaling, without introducing mean frequency shifts in the minimal version.

Crucially, the beable is not introduced to alter ensemble outcome frequencies: those remain Born-rule by construction of the pointer unraveling. Instead, $n(t)$ provides (i) an ontological referent for the internal spin orientation carried by the excitation and (ii) a controlled, testable route to contextual record-level deviations through the small parameter ε , which modulates the effective measurement axis $\hat{a}_{\text{eff}}(t)$ without shifting the Zeeman/Larmor dynamics in the minimal version.

Minimal limit ($\varepsilon = 0$). In the strict $\varepsilon = 0$ limit the Beable Theory is operationally equivalent to orthodox continuous-measurement / quantum-trajectory dynamics for a monitored qubit: the beable provides an ontological referent for internal orientation ($n(t) \in S^3$ with base-space image $\vec{r}(t) \in S^2$) but introduces no deviation in ensemble outcome frequencies or Zeeman precession. Distinct empirical content enters only through record-level statistics when $\varepsilon \neq 0$ and/or through an always-on background channel $\kappa_{\text{bg}} > 0$.

2. Conceptual Background

Spin-1/2 superposition is often presented as a system being 'in two states at once'. In practice, the theory assigns a spinor $|\psi\rangle$ whose components in a chosen basis interfere. Our starting point is to reify an internal orientation field $n(t)$ (a beable) that drives coherent precession of the spinor. The model remains operationally quantum in that it uses the usual state vector and Hamiltonian evolution, but it supplements the ontology by specifying (a) an internal orientation and (b) a pointer-localization collapse channel. We restrict to the following dynamics: ensemble-level pure dephasing plus single-run selection at collapse, excluding intrinsic spontaneous spin flips in isolation.

3. Ontological Postulates

Postulate O1 (electron as field excitation). Electrons are treated as excitations of the electron field. The model is compatible with standard QFT in the sense that it does not alter the field content; it adds an internal beable carried by the excitation.

Postulate O2 (spinor-bundle beable n). Each electron excitation carries a real internal beable $n(t)$ that lives in the spinor bundle: $n(t) \in S^3$. Its gauge-invariant, operational image is the Bloch vector $\vec{r}(t) \in S^2$ obtained by the Hopf projection. Only $\vec{r}(t)$ may enter observable couplings unless an external phase reference is supplied; the fiber phase $\chi(t)$ is treated as gauge. For the benchmark regimes considered here, $\vec{r}(t)$ can be taken as slowly varying (or piecewise constant) on the measurement timescale.

A normalized spin- $\frac{1}{2}$ pure state is represented by a unit spinor $|\psi\rangle \in \mathbb{C}^2$ with $\langle\psi|\psi\rangle = 1$. The space of normalized spinors is the 3-sphere S^3 . Physical spin orientations correspond to points on the Bloch sphere S^2 via the Hopf map: $r^\rightarrow(|\psi\rangle) = \langle\psi|\sigma^\rightarrow|\psi\rangle$, with $|r^\rightarrow| = 1$. Two spinors differing by a global phase $e^{i\chi}$ map to the same Bloch vector r^\rightarrow , so the phase χ parameterizes a $U(1)$ fiber over S^2 . Globally, this is the Hopf fibration $S^1 \hookrightarrow S^3 \rightarrow S^2$.

Beable choice (spinor-bundle). We take the beable $n(t)$ to be a point in the total space S^3 , i.e., the normalized spinor itself, or equivalently an $SU(2)$ element $g(t)$ acting on a reference spinor. The gauge-invariant ‘orientation’ is $r^\rightarrow(t)$, while the fiber coordinate $\chi(t)$ tracks internal phase information that is normally unobservable in orthodox quantum mechanics unless a phase reference is supplied by the apparatus.

Postulate O3 (pointer realism). Whenever information about a spin observable is amplified into a record—via an apparatus, environment, or other fields—there exists a physically instantiated pointer variable X (e.g., a detector current, resonator field, or frequency-estimation record) that differentiates the outcomes.

Postulate O4 (collapse localizes the pointer). Objective collapse acts by stochastically localizing the pointer variable X . Spin-state definiteness is emergent: when the spin becomes entangled with distinct pointer branches, pointer localization forces single-run selection.

4. Dynamical Model

4.1 Coherent Evolution: Zeeman Dynamics and an Ontic Orientation Beable

In standard quantum mechanics, coherent ‘wheel-like’ rotation of the Bloch vector in a magnetic field is generated by the Zeeman Hamiltonian $H_Z = -\mu \cdot B = (\hbar \Omega_L/2) \sigma \cdot \hat{b}$, where \hat{b} is the unit vector along the total magnetic field and Ω_L is the Larmor angular frequency. Our model does not seek to replace this well-tested dynamics.

Minimal (main) reading—ontological reinterpretation. We introduce the internal orientation beable $n(t)$ as an ontic representation of the spin-frame/phase associated with Zeeman evolution. In this minimal version, the unitary dynamics is $H_{\text{unitary}} \equiv H_Z$ and we identify $S \equiv \Omega_L$. No additional precession term is introduced and no new frequency shift is predicted; the beable supplies a realist referent for the evolving phase without modifying QED.

In the minimal model, coherent evolution is governed by the standard Zeeman Hamiltonian $H_Z = (\hbar \Omega_L/2) \sigma \cdot \hat{b}$, where \hat{b} is the unit vector along the total magnetic field. The spinor evolves as $|\psi(t)\rangle = \exp[-(i/\hbar) H_Z t] |\psi(0)\rangle$. On the base S^2 , this induces the usual Larmor precession of $r^\rightarrow(t)$ about \hat{b} at angular rate Ω_L . On the total space S^3 , this is a smooth bundle transport that also advances the fiber phase $\chi(t)$. If $\hat{b}(t)$ varies slowly in time, $\chi(t)$ contains both dynamical and geometric (Berry) contributions. Crucially, in the minimal model this geometry does not introduce any extra observable precession frequency; it is an ontological refinement, not a new torque.

Optional extended reading—additional intrinsic precession (for falsifiability only). One may consider a small correction $H_{\text{int}}(t) = (\hbar \delta\Omega_{\text{int}}/2) \sigma \cdot n(t)$ added to H_Z , with $|\delta\Omega_{\text{int}}| \ll \Omega_L$. This would shift the observed precession/anomaly frequency by $\approx \delta\Omega_{\text{int}} \cos\theta$ (θ the angle between n and \hat{b}) and is therefore tightly constrained by precision g -factor spectroscopy. We treat $\delta\Omega_{\text{int}}$ as an optional extension and do not require it for the benchmark fits reported below.

4.2 Measurement Interaction and Pointer Entanglement

To represent the emergence of a measurement record, we couple the electron spin to a pointer degree of freedom X through a von Neumann-type interaction.

Role 1 (operational): the carried beable $n(t)$ slightly modulates the effective measurement axis. We define

$$H_{\text{meas}} = \hbar g (\sigma \cdot \hat{a}_{\text{eff}}(t)) \otimes P_X, \text{ with } \hat{a}_{\text{eff}}(t) = \mathcal{N}(\hat{a} + \varepsilon \Pi_{\perp}(\vec{r}(t))).$$

where \hat{a} is the apparatus-defined axis, Π_{\perp} projects n onto the plane perpendicular to \hat{a} , \mathcal{N} denotes normalization, and $\varepsilon \ll 1$ is a dimensionless basis-modulation strength. This construction makes $n(t)$ empirically relevant through measurement backaction while leaving mean Zeeman precession unchanged.

The interaction correlates spin eigenstates along \hat{a}_{eff} with distinguishable pointer states $|X_{\pm}\rangle$, producing $|\psi\rangle|X_0\rangle \rightarrow \alpha|+\hat{a}_{\text{eff}}\rangle|X_+\rangle + \beta|-\hat{a}_{\text{eff}}\rangle|X_-\rangle$.

The beable's only operational footprint is through the effective measurement axis $\hat{a}_{\text{eff}}(t)$, hence through the measured observable $M(t) = \sigma \cdot \hat{a}_{\text{eff}}(t)$. Under the gauge-invariant choice, $\hat{a}_{\text{eff}}(t)$ depends only on the Bloch-vector image $\vec{r}(t)$ of the spinor-bundle beable $n(t) \in S^3$ and never on the fiber phase $\chi(t)$. This preserves standard Zeeman dynamics and avoids introducing any extra precession frequency: the beable does not add a new Hamiltonian torque; it weakly modulates the collapse basis during record formation.

Gauge-invariant coupling. We define the effective measurement axis as $\hat{a}_{\text{eff}}(t) = \mathcal{N}(\hat{a} + \varepsilon \Pi_{\perp}(\vec{r}(t)))$, where $\Pi_{\perp}(\vec{r}) = \vec{r} - (\vec{r} \cdot \hat{a})\hat{a}$ projects onto the plane orthogonal to \hat{a} and $\varepsilon \ll 1$ is a basis-modulation parameter. This choice is gauge-invariant (depends only on $\vec{r}(t) \in S^2$, not on the fiber phase $\chi(t)$) and therefore does not introduce a new Zeeman torque or measurable frequency shift in the minimal model. Its novelty appears in trajectory-level pointer records rather than in mean precession.

Why this yields exactly two outcomes: In the pointer-localized framework, collapse acts through the measurement channel associated with the Hermitian operator $\sigma^{\vec{r}} \cdot \hat{a}_{\text{eff}}(t)$. Regardless of how \hat{a}_{eff} is modulated, $\sigma^{\vec{r}} \cdot \hat{a}_{\text{eff}}$ has exactly two eigenvalues ± 1 with eigenstates $|\pm \hat{a}_{\text{eff}}\rangle$. Thus the measurement-record branching and the pointer localization always produce one of two stable branches in a single run. The key conceptual point is that the 'two-valuedness' of outcomes is a spectral property of the measured spin operator, not a statement that the beable itself is discrete. The beable can be continuous (S^3) while collapse yields binary outcomes.

4.3 Objective Localization of the Pointer and Reduced Spin Dynamics

We model objective collapse as a localization channel acting on the pointer coordinate X . At the ensemble level, a generic translation-covariant localization superoperator yields:

$$d\rho/dt = -(i/\hbar)[H_{\text{unitary}} + H_{\text{meas}} + H_{\text{ptr}}, \rho] - (\Lambda(t)/2) [X, [X, \rho]]$$

where $\Lambda(t)$ is a localization strength (units of $s^{-1} \cdot X^{-2}$) and H_{ptr} is the pointer's Hamiltonian. We decompose

$$\Lambda(t) = \Lambda_{\text{bg}} + \Lambda_{\text{ext}}(t),$$

Objective localization is modeled as continuous weak monitoring of the pointer coordinate X , producing a translation-covariant localization channel with total strength $\Lambda(t) = \Lambda_{\text{bg}} + \Lambda_{\text{ext}}(t)$.

When the spin becomes entangled with pointer branches separated by ΔX , tracing out the pointer yields an effective reduced-spin pure-dephasing equation in the instantaneous measurement basis set by $\hat{a}_{\text{eff}}(t)$.

$$d\rho_s/dt = -(i/\hbar)[H_{\text{unitary}}, \rho_s] + (\kappa(t)/2) [(\sigma \cdot \hat{a}_{\text{eff}}) \rho_s (\sigma \cdot \hat{a}_{\text{eff}}) - \rho_s]$$

with the identification (up to model-dependent geometric factors):

$$\kappa(t) \approx (\Lambda(t)/2) (\Delta X)^2 = \kappa_{\text{bg}} + \kappa_{\text{meas}}(t).$$

Thus, in the measurement basis, the spin off-diagonals decay as $\exp[-\kappa(t) t]$, while single-run definiteness occurs through the diffusive pointer-localization trajectory (see Section 4.4).

We model the measurement record as arising from a quantum ‘‘pointer’’ degree of freedom with position operator X and conjugate momentum P . The total Hamiltonian is $H = H_{\text{unitary}} + H_{\text{meas}} + H_{\text{ptr}}$, where H_{unitary} is the coherent spin Hamiltonian ($H_{\text{unitary}} \equiv H_Z$), H_{ptr} is the free pointer Hamiltonian (e.g., $P^2/2m$ or an effective harmonic mode), and the spin–pointer coupling is $H_{\text{meas}} = \hbar g (\sigma \cdot \hat{a}_{\text{eff}}(t)) \otimes P$, so that spin eigenstates of $\sigma \cdot \hat{a}_{\text{eff}}$ correlate with oppositely displaced pointer wavepackets. For an initial spin state $|\psi_s\rangle = \alpha|+\hat{a}_{\text{eff}}\rangle + \beta|-\hat{a}_{\text{eff}}\rangle$ and an initial pointer packet $|\varphi_0\rangle$, the unitary part generates $|\Psi\rangle = \alpha|+\hat{a}_{\text{eff}}\rangle|\varphi_+\rangle + \beta|-\hat{a}_{\text{eff}}\rangle|\varphi_-\rangle$, where the two pointer packets have mean separation $\Delta X \equiv \langle X \rangle_+ - \langle X \rangle_-$.

Objective localization is represented as continuous weak monitoring of X , yielding the translation-covariant master equation $d\rho/dt = -(i/\hbar)[H, \rho] - (\Lambda(t)/2)[X, [X, \rho]]$. For two pointer branches separated by ΔX , the pointer off-diagonals decay as $\exp[-(\Lambda/2)(\Delta X)^2 t]$, producing the reduced-spin dephasing rate $\kappa(t) \approx (\Lambda/2)(\Delta X)^2$. For an isolated spin with no pointer separation, $\Delta X \rightarrow 0$ and no collapse occurs, consistent with the pointer-first mechanism.

For simulations and inference it is convenient to work in the reduced-spin description where the pointer has been eliminated. Let $M(t) = \sigma \cdot \hat{a}_{\text{eff}}(t)$ with $\hat{a}_{\text{eff}}(t) = \mathcal{N}(\hat{a} + \varepsilon \Pi_{\perp}(r^{\vec{r}}(t)))$ and $\varepsilon \ll 1$. The unconditional evolution reads $d\rho_s = -(i/\hbar)[H_{\text{unitary}}, \rho_s] dt + 2k \mathcal{D}[M(t)]\rho_s dt$, with $\mathcal{D}[M]\rho = M\rho M - \frac{1}{2}(M^2\rho + \rho M^2)$.

4.4 Stochastic Unraveling, Single-Run Selection, and the Born Rule

The unconditional equation admits standard diffusive unravelings corresponding to continuous measurement of X . A normalized SSE (Ito form) is: $d|\Psi\rangle = [-(i/\hbar)H - (\Lambda/2)(X - \langle X \rangle)^2] |\Psi\rangle dt + \sqrt{\Lambda} (X - \langle X \rangle) |\Psi\rangle dW_t$, where dW_t is a Wiener increment with $E[dW_t] = 0$ and $E[(dW_t)^2] = dt$. Ensemble averaging over trajectories recovers the master equation: $\rho(t) = E[|\Psi(t)\rangle\langle\Psi(t)|]$.

The associated measurement record (pointer readout) can be written as an observed classical signal $R(t)$ whose increments satisfy $dR_t = 2\sqrt{\Lambda} \langle X \rangle_c dt + dW_t$, where $\langle \cdot \rangle_c$ denotes the conditional expectation given the record up to time t . Thus the fundamental ‘pointer noise’ is Gaussian white noise (the innovation process dW_t), while its effect on the state is multiplicative through $(X - \langle X \rangle)$.

Born-rule status. The outcome frequencies are not taken as an independent axiom here; rather, they follow from the diffusive stochastic dynamical postulate used to model objective pointer monitoring. In this setting the branch weights are martingales under the conditioned evolution, implying that the probability of eventual localization to a given branch equals its initial Born weight. This is a standard result in quantum trajectory theory; our contribution is to treat the trajectory dynamics as an ontological collapse mechanism for a physically instantiated pointer, rather than as a mere numerical unraveling.

Concretely, in the regime where the measurement interaction produces two well-separated pointer packets correlated with spin eigenstates, the conditional state takes the schematic form $|\Psi\rangle = \alpha|+\rangle|\varphi_+\rangle + \beta|-\rangle|\varphi_-\rangle$. Under the diffusive stochastic evolution, the branch weight $p_+(t) = \langle \Psi(t) | \Pi_+ | \Psi(t) \rangle$ is a martingale, so $\mathbb{E}[p_+(t)] = p_+(0) = |\alpha|^2$. As $t \rightarrow \infty$ the dynamics drives $p_+(t) \rightarrow 0$ or 1 on individual runs (pointer selection), hence $\text{Prob}(+ \text{ branch}) = |\alpha|^2$ and $\text{Prob}(- \text{ branch}) = |\beta|^2$.

A diffusive unraveling gives the conditional (single-run) evolution $d\rho_s = -(i/\hbar)[H_{\text{unitary}}, \rho_s] dt + 2k \mathcal{D}[M(t)]\rho_s dt + \sqrt{2k} \mathcal{J}[M(t)]\rho_s dW_t$, where $\mathcal{J}[M]\rho = M\rho + \rho M - 2\langle M \rangle_c \rho$ for Hermitian M . The associated (ideal) measurement record may be written $dR_t = 2\sqrt{2k} \langle M(t) \rangle_c dt + dW_t$.

Because the record is $dR_t = 2\sqrt{\Lambda} \langle X \rangle_c dt + dW_t$, the innovation dW_t is Gaussian with flat (white) spectrum, while $\langle X \rangle_c(t)$ becomes a stochastic process that rapidly approaches one of the two branch values $\langle X \rangle_{\pm}$. In the two-branch regime this yields: Mean record conditioned on the outcome, $\langle X \rangle_c(t) \rightarrow \langle X \rangle_{\pm}$ and the record approaches a line with drift $2\sqrt{\Lambda} \langle X \rangle_{\pm}$ plus white noise. Variance and dwell-time statistics: During the transient, the multiplicative term $\sqrt{\Lambda} (X - \langle X \rangle)$ amplifies fluctuations when $\text{Var}(X)$ is large, and the state purifies as $\text{Var}(X)$ shrinks. This predicts a characteristic narrowing of record variance synchronized with branch selection.

Link to the ε parameter. If $\hat{a}_{\text{eff}}(t) = \mathcal{N}(\hat{a} + \varepsilon \Pi_{\perp}(\vec{r}(t)))$ differs slightly from the apparatus axis \hat{a} , then repeated runs prepared in the same nominal spin state can exhibit subtle contextual deviations in record-level statistics (variance, dwell times, higher cumulants) even when ensemble mean outcomes remain Born-like.

Consistency with precision spectroscopy and no-go theorems: Because the spinor-bundle beable is an ontological refinement of standard Zeeman dynamics, it does not induce frequency shifts excluded by precision $g-2$ measurements. Empirical novelty enters only via the measurement coupling (ε) and the objective pointer-localization channel (Λ), bounded by linewidth and record statistics. The model does not posit a local deterministic hidden variable; it provides a realist account of internal phase/orientation while preserving Born statistics via stochastic pointer localization. Accordingly, it is not in direct conflict with Bell/Kochen–Specker no-go results, though $\varepsilon \neq 0$ represents a controlled form of measurement contextuality at the level of record dynamics.

4.5 Relation to Diósi–Penrose–Style Gravity-Induced Collapse

If one interprets part of the localization strength as gravity-mediated (DP-like), one may write $\Lambda = \Lambda_{\text{bg}} + \Lambda_{\text{ext}}$, where Λ_{bg} is ‘always on’ and Λ_{ext} is measurement-amplified. In DP-type models, localization in position is driven by mass-density differences between branches, and a common scaling is $\kappa_{\text{DP}} \sim \Delta E_G / \hbar$ for macroscopically distinct mass distributions. In the present pointer-first

framework, gravity would primarily act on the pointer/mass-density branches rather than on an isolated spin ($\Delta X \approx 0$), consistent with the trapped-electron linewidth bound on κ_{bg} .

5. Empirical Benchmarks

Using published trapped-electron spectroscopy data (Fan et al., Phys. Rev. Lett. 130, 071801 (2023)) we translate the reported anomaly linewidth budget into an explicit upper bound $\kappa_{bg} \lesssim 5 \times 10^{-2} s^{-1}$ (order-of-magnitude; see digitization appendix), with a more conservative bound $\kappa_{bg} \lesssim 2 \times 10^{-1} s^{-1}$ from the full observed linewidth. As a secondary benchmark, we show that the functional scaling expected in the strong-measurement (quantum Zeno) regime of circuit QED (Slichter et al., New J. Phys. 18, 053031 (2016)) is consistent with the model's measurement-induced dephasing structure.

6. Unified Stochastic Model, Predictions, and Simulation Program This constraint is intentionally conservative: it attributes any unexplained residual linewidth budget to κ_{bg} , so improved access to raw records and noise spectra can only tighten the bound.

6.1 Nexus and unified operational chain

This section assembles the Beable Theory into a single operational chain from ontology to data. The beable is an ontic spinor-bundle variable $n(t) \in S^3$ whose gauge-invariant image $r^\rightarrow(t) \in S^2$ modulates the effective measurement axis $\hat{a}_{eff}(t) = \mathcal{N}(\hat{a} + \varepsilon \Pi_\perp(r^\rightarrow(t)))$. The monitored observable $M(t) = \sigma \cdot \hat{a}_{eff}(t)$ determines the stochastic pointer record. Novelty therefore appears in record-level statistics and transient dynamics (controlled by ε and κ_{bg}), while ensemble outcome frequencies remain Born-like under the martingale property of branch weights.

6.2 Unified stochastic equations

Define the Hermitian monitored observable $M(t) = \sigma \cdot \hat{a}_{eff}(t)$. The unconditional evolution of the reduced spin is

$$d\rho_s = -(i/\hbar)[H_{unitary}, \rho_s] dt + 2k(t) \mathcal{D}[M(t)]\rho_s dt + \mathcal{L}_{bg}[\rho_s] dt,$$

where $\mathcal{D}[M]\rho = M\rho M - \frac{1}{2}(M^2\rho + \rho M^2)$, $k(t)$ is the measurement/localization strength, and \mathcal{L}_{bg} is any always-on background channel. A diffusive unraveling yields conditional single-run trajectories

$$d\rho_s = -(i/\hbar)[H_{unitary}, \rho_s] dt + 2k(t) \mathcal{D}[M(t)]\rho_s dt + \sqrt{2k(t)} \mathcal{J}[M(t)]\rho_s dW_t,$$

with $\mathcal{J}[M]\rho = M\rho + \rho M - 2\langle M \rangle_c \rho$ and Wiener increments dW_t satisfying $\mathbb{E}[dW_t] = 0$ and $\mathbb{E}[(dW_t)^2] = dt$. An idealized measurement record can be written

$$dR_t = 2\sqrt{2k(t)} \langle M(t) \rangle_c dt + dW_t.$$

6.3 Testable signatures

The Beable Theory makes three empirically distinct claims. (i) Born stability: ensemble outcome frequencies remain Born-like because branch weights are martingales under the diffusive unraveling. (ii) Record-level novelty: for $\varepsilon \neq 0$ the pointer record statistics (variance growth, dwell-time distributions, higher cumulants, and filtered PSDs) acquire weak state- and axis-dependence beyond the orthodox $\varepsilon = 0$ case, even when mean outcomes are unchanged. (iii) Background bound: any always-on κ_{bg} contributes to linewidth and record-noise budgets, enabling conservative upper bounds from precision experiments.

6.4 Simulation and inference program

To translate the above into concrete parameter bounds on $(\epsilon, \kappa_{\text{bg}}, k)$, we propose a reproducible Monte Carlo program:

1. Specify platform: choose H_{unitary} (Zeeman \pm drive), measurement axis \hat{a} , and a measurement schedule $k(t)$.
2. Initialize the state: select initial spin $\rho_s(0)$ and (if needed) an initial beable state $n(0)$ (equivalently $r^{\vec{}}(0)$).
3. Evolve trajectories: integrate the diffusive SME/SSE (Euler–Maruyama) to generate conditional states and records $R(t)$ for N runs.
4. Extract observables: collapse-time distribution $P(t_c)$ from a threshold on $|\langle M \rangle_c|$, dwell-time statistics, and record cumulants/PSD.
5. Ensemble checks: verify Born frequencies and reproduce orthodox limits when $\epsilon=0$.
6. Fit/bound parameters: compare simulated summaries to published linewidth budgets, switching rates, or record statistics to infer limits on ϵ and κ_{bg} .
7. Robustness: repeat under timestep reduction and alternative filters to ensure stability of bounds.

Detection efficiency ($\eta < 1$). In realistic implementations the measurement record is not perfectly efficient. A standard model introduces an efficiency factor $\eta \in (0, 1]$ such that the informational component of the record is reduced, $dR_t = 2\sqrt{2\eta k(t)} \langle M(t) \rangle_c dt + dW_t$, and the innovation term in the SME is rescaled by $\sqrt{\eta}$. Lower η weakens the statistical power to bound ϵ from higher-order record cumulants, but does not alter unconditional linewidth/dephasing constraints used for κ_{bg} bounds.

6.5 Public-data compatibility

Even when raw measurement records are not available, the program yields informative constraints. Linewidth budgets and reported dephasing rates bound κ_{bg} conservatively, while switching-rate parameters and reported PSDs (when available) allow direct comparison to simulated record summaries. When open trajectory datasets exist, the same pipeline upgrades from bounding to parameter estimation.

Scenario	Outcome ($P(+z)$, $P(-z)$)	freq. Collapse-time stats (mean / median / std; $P(tc < 0.1)$, $P(tc < 0.2)$)
$\epsilon=0$ (orthodox)	0.527, 0.473	0.218 / 0.175 / 0.160; 0.210, 0.603
$\epsilon=0.05$ (gauge-invariant $\hat{a}_{\text{eff}}(r^{\vec{}})$ modulation)	0.490, 0.510	0.218 / 0.179 / 0.146; 0.177, 0.580

7. Discussion and Compatibility

In this work, we have presented the Beable Theory as a unified framework that combines an oscillatory beable with pointer-localized objective collapse to address the quantum measurement problem in the context of electron spin superpositions. The model is designed to be phenomenologically conservative, preserving the well-tested predictions of standard quantum mechanics and QED while introducing ontological clarity and testable extensions.

A central question is the role of the beable $n(t)$. Phenomenologically, if one assumes the Born-rule statistics, the beable might appear silent in mean outcomes. However, it serves two key purposes. Ontologically (Role 3), $n(t)$ —modeled on the spinor bundle $S^3 \rightarrow S^2$ —provides a realist representation of the internal spin-frame/phase associated with Zeeman evolution. This allows the coherent-to-classical transition to be described within a single ontology, treating the evolving relative phase as a property of the electron excitation rather than a purely epistemic construct. Operationally (Role 1), $n(t)$ influences dynamics through gauge-invariant modulation of the effective measurement axis $\hat{a}_{\text{eff}}(t) = \mathcal{N}(\hat{a} + \varepsilon \Pi_{\perp}(\vec{r}(t)))$, introducing axis-dependent corrections to backaction and dephasing parameterized by ε . This yields subtle, falsifiable signatures in trajectory-level pointer-record statistics (e.g., variance, dwell times, higher cumulants) without altering mean Zeeman precession or ensemble Born probabilities.

The basis-modulation parameter ε encodes a controlled deviation from the orthodox view that the measurement basis is determined solely by the apparatus axis \hat{a} . For $\varepsilon \neq 0$, while mean outcome frequencies remain Born-like, the pointer record acquires weak contextual dependence on the internal orientation/phase through $\hat{a}_{\text{eff}}(t)$. This offers experimental falsifiability: dedicated protocols involving axis rotations or controlled measurement strength can probe for small anomalies in backaction and noise absent in $\varepsilon = 0$ models. Bounds from public data are consistent with $\varepsilon \approx 0$ at the plot level, but targeted datasets could constrain ε to order 10^{-2} – 10^{-3} .

Compatibility with no-go theorems is ensured because $n(t)$ does not deterministically fix outcomes; the model preserves Born statistics via stochastic pointer localization and martingale branch weights. It does not posit a local deterministic hidden-variable theory vulnerable to Bell inequalities. Instead, it augments quantum state evolution with (i) objective pointer localization and (ii) basis-modulated backaction during record formation. Any $\varepsilon \neq 0$ introduces mild measurement contextuality at the record level, but this is empirically bounded and does not conflict with Kochen-Specker results, as the beable is not a value-definite assignment to all observables.

On contextuality and linearity. The basis-modulation parameter ε is introduced as a phenomenological handle that renders the theory falsifiable at the level of measurement records. Importantly, $\hat{a}_{\text{eff}}(t)$ is not assumed to be a functional of the quantum state as an epistemic object; rather, it is conditioned on an ontic beable trajectory (equivalently its gauge-invariant projection $\vec{r}(t)$). The underlying system+apparatus dynamics may remain linear, while the reduced conditioned description acquires the usual effective nonlinearity associated with conditioning on a measurement record. In the conservative $\varepsilon \rightarrow 0$ limit the model reduces to orthodox continuous-measurement dynamics.

Possible microphysical origins of ε include small transverse components in realistic spin–pointer couplings, finite bandwidth and filtering in the amplification chain that induces a weak axis-bias correlated with the beable orientation, or higher-order detector backaction terms that vanish in the idealized limit. The present work treats ε as a controlled parameter to be bounded (or estimated) from record-level statistics.

The pointer-first mechanism aligns with long spin coherence times in isolated systems, as collapse requires pointer-branch separation ($\Delta X \neq 0$); bare spin superpositions without amplification or environmental imprinting remain coherent. This resolves a common critique of objective-collapse models like GRW/CSL, where direct collapse on microscopic degrees of freedom would disrupt delicate superpositions prematurely.

Regarding Diósi–Penrose (DP) compatibility, the background channel κ_{bg} can be identified with a gravity-related rate $\kappa_{\text{DP}} \approx \Delta E_{\text{G}} / \hbar$, where ΔE_{G} is the gravitational self-energy difference between mass-density distributions of pointer branches. In this framework, gravity acts primarily on macroscopic records rather than isolated spins (where $\Delta X \approx 0$ and ΔE_{G} is negligible), suppressing macroscopic superpositions while leaving microscopic coherence intact. The derived bound $\kappa_{\text{bg}} \lesssim 5 \times 10^{-2} \text{ s}^{-1}$ from trapped-electron data constrains any DP-like mechanism acting directly on the electron in the Penning-trap context, but is consistent with DP's focus on mass-density.

Future extensions could include (i) deriving the Born rule from a microscopic pointer model beyond the martingale postulate, (ii) incorporating phase-sensitive couplings involving the fiber coordinate $\chi(t)$ in homodyne setups, (iii) exploring relativistic generalizations tying the beable to Zitterbewegung or Dirac spinors, and (iv) applying the simulation program to raw trajectory data for joint ε - κ_{bg} inference. The Beable Theory thus provides a testable bridge between quantum foundations and precision experiments, with ε and κ_{bg} as levers for empirical scrutiny.

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