Hyperfine Spectroscopy as Collapse-Selection Structure

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Purpose. This note provides a direct correspondence between high-precision spectroscopic Hamiltonians and the collapse-selection framework of Quantum Collapse Geometry (QCG), situating observable spectral structure as the residue of admissible relational dynamics.

Framework. Let Σ denote a relational configuration space and

$$\Phi : \Sigma \to \Sigma$$

a collapse-selection operator. Observable structure arises through a projection

$$P : \Sigma \to \mathcal{O}_\lambda$$

onto a coarse-grained state space at observational scale λ.

We assume an induced effective evolution

$$P \circ \Phi \;\approx\; E_\lambda \circ P,$$

with generator G_λ on $\mathcal{O}_\lambda$. Within QCG, G_λ is not fundamental, but encodes the observable residue of collapse-selection under constraint.

Proposition (Hamiltonian Correspondence). Let Φ and P be as above. Any Hamiltonian H governing observed dynamics on $\mathcal{O}_\lambda$ may be consistently interpreted as a scale-local generator

$$H \sim G_\lambda[\Phi; P],$$

whose spectral decomposition partitions $\mathcal{O}_\lambda$ into collapse-stable invariant sectors under Φ.

Interpretation.

- Observable states correspond to projected relational configurations:

$$o \sim P(x), \quad x \in \Sigma.$$

- Eigenstates of H correspond to invariant sectors under Φ:

$$H\psi_i = E_i\psi_i \iff \psi_i \sim P(x_i),\; x_i \in \mathrm{Inv}(\Phi).$$

- Transition structure reflects accessibility between admissible sectors under perturbed collapse dynamics.
- Hamiltonian parameters encode constraint structure:
  - internal couplings $\to$ relational compatibility,
  - external fields $\to$ admissibility shaping,
  - spectral gaps $\to$ invariant sector separation.

Relational configuration space Σ
Relational spin configurations under coupling and field constraint

$\Downarrow\ \Phi$

collapse-selection

Admissible / invariant sector $\mathrm{Inv}(\Phi)$
Collapse-stable relational structure

$\Downarrow\ P$

descriptive projection

Observable sector $\mathcal{O}_\lambda$
Hyperfine levels, spin labels, transition structure

$\Downarrow\ G_\lambda \sim H$

scale-local generator / effective Hamiltonian

Measured outcomes
Resonances, spectral gaps, collapse-stable measurement sectors

Figure 1: Schematic relation between collapse-selection dynamics and spectroscopic description in QCG. The primitive collapse operator Φ acts on the relational configuration space Σ, selecting admissible invariant structure. Descriptive projection P maps this structure to the observable sector $\mathcal{O}_\lambda$, where the scale-local generator G_λ is represented effectively by the spectroscopic Hamiltonian H. Measured outcomes correspond to transitions between and identification of collapse-stable sectors.

Categorical Context. This structure admits a natural realization in CPM(**FHilb**), where completely positive maps represent effective collapse channels, and G_λ corresponds to the observable residue of a collapse comonad acting on relational configurations.

Remark (Measurement as Coalgebra). Let

$$\mathrm{Coll} : \mathcal{C} \to \mathcal{C}$$

be the lax idempotent comonad induced by admissible collapse dynamics. Measurement outcomes correspond to coalgebras

$$\gamma : x \to \mathrm{Coll}(x),$$

with stable configurations satisfying

$$\mathrm{Coll}(x) \cong x.$$

Thus, measurement identifies collapse-stable structure rather than generating it, and observable states form the coreflective subcategory of Coll-coalgebras.

Example (HD^+ Hyperfine Structure). We consider the high-precision Penning-trap spectroscopy of HD^+ reported in [1], in which the effective Hamiltonian

$$H = hE_4(I_p \cdot s_e) + hE_5(I_d \cdot s_e) - \mu_B g_e(B \cdot s_e) - \mu_B g_p(B \cdot I_p) - \mu_B g_d(B \cdot I_d)$$

as used to describe the hyperfine structure in the rovibrational ground state. [1]

In QCG:

- Σ encodes relational spin configurations under constraint,
- Φ enforces admissibility via coupling and field structure,
- P maps to observable spin sectors $(m_s, m_{I,p}, m_{I,d})$,
- eigenstates correspond to collapse-stable sectors,
- resonances probe transition accessibility between these sectors, as implemented through repeated single-ion spin-flip measurements and likelihood-based reconstruction of transition frequencies [1].

Conclusion. High-precision spectral structure may be interpreted as the observable partition of relational configuration space into invariant sectors under collapse-selection. Hamiltonians provide scale-local generators of this structure, while measurement identifies its coalgebraic fixed points. This establishes a direct bridge between experimental spectroscopy and the generative ontology of QCG. This correspondence does not derive the Hamiltonian from collapse-selection, but identifies it as a consistent effective representation of admissible relational structure at fixed observational scale.

References

[1] Charlotte M. König et al. "High-Precision Penning Trap Spectroscopy of the Ground State Spin Structure of HD^+". In: *Phys. Rev. Lett.* 136 (14 Apr. 2026), p. 143002. DOI: 10.1103/vrl8-bpmz. URL: https://link.aps.org/doi/10.1103/vrl8-bpmz.