# Discriminating Spectral Diffusion from Charge-State Ionization in Single-Shot Spin Readout Fluctuations

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## ABSTRACT

We address the open question of whether intermittent disappearance and reappearance of single-shot spin readout fluctuations in cavity-coupled silicon-vacancy centers arises from spectral diffusion or ionization into a dark charge state. Using simulated telegraph traces, we apply Bayesian model comparison of dwell-time distributions, Hidden Markov Model classification, statistical discrimination metrics, and temperature-dependent analysis to distinguish these mechanisms. Spectral diffusion produces stretched-exponential bright dwell times ($\beta = 0.627$) with high coefficient of variation (CV= 1.64), while ionization yields near-exponential statistics ($\beta \approx 0.99$, CV= 0.99). Bayesian evidence strongly favors stretched exponentials for spectral diffusion (log Bayes factor = −637) but is inconclusive for ionization bright dwells (log Bayes factor = 0.66). HMM classification achieves 43.2% accuracy for spectral diffusion versus 41.3% for ionization traces, with the spectral diffusion model showing consistently higher log-likelihood (−3109 vs. −3187). Temperature dependence reveals that duty cycle drops from 100% below 2 K to 9.5% at 20 K with RMS detuning scaling as $T^{1.5}$, consistent with phonon-driven spectral diffusion.

## 1 INTRODUCTION

Single-shot spin readout is essential for quantum information processing with solid-state defects [1, 2]. In cavity-coupled silicon-vacancy (SiV) centers in diamond, Yama et al. [10] observed that fluctuations associated with spin thermalization intermittently disappear and reappear during data acquisition. This behavior reduces readout fidelity and complicates spin dynamics interpretation.

Two candidate mechanisms could produce this intermittent behavior: (i) spectral diffusion of the optical transition, where the emitter frequency wanders relative to the cavity resonance due to fluctuating local charge or strain environments [5], and (ii) ionization into a dark charge state, where the SiV transitions to $SiV^0$ or another non-fluorescent charge configuration [3]. Distinguishing these mechanisms is critical for developing mitigation strategies.

### 1.1 Related Work

Group-IV defects in diamond have emerged as leading platforms for quantum networking [6, 7, 9]. Spectral diffusion has been characterized using photoluminescence excitation spectroscopy [5], while charge-state dynamics have been studied in nitrogen-vacancy centers [4]. Hidden Markov Models provide a natural framework for analyzing telegraph-like switching [8].

## 2 METHODS

### 2.1 Stochastic Simulation

We generate synthetic cavity transmission traces under both mechanisms. For spectral diffusion, the emitter detuning follows an Ornstein-Uhlenbeck process with correlation time $\tau_c = 0.5$ s and RMS width $\sigma = 5$ GHz. The transmission depends on detuning as $T(\delta) = T_0/(1 + (\delta/\kappa)^2)$ with cavity linewidth $\kappa = 10$ GHz. For charge-state ionization, the emitter switches between bright ($SiV^-$) and dark ($SiV^0$) states with ionization rate $\gamma_{\text{ion}} = 0.3\ \text{s}^{-1}$ and recombination rate $\gamma_{\text{rec}} = 2.0\ \text{s}^{-1}$.

**Table 1: Dwell-time distribution parameters and Bayesian model comparison.**

| Mechanism | State | $\beta$ | $\tau$ [s] | log BF |
|---|---|---|---|---|
| Spectral diff. | Bright | 0.627 | 0.831 | −637 |
| Spectral diff. | Dark | 0.818 | 0.263 | −118 |
| Ionization | Bright | 0.990 | 3.308 | +0.66 |
| Ionization | Dark | 1.158 | 0.518 | −13.2 |

### 2.2 Dwell-Time Analysis

Bright and dark dwell times are extracted via threshold crossing. We fit both exponential $f(t) = \lambda e^{-\lambda t}$ and stretched-exponential $f(t) = (\beta/\tau)(t/\tau)^{\beta-1} e^{-(t/\tau)^\beta}$ distributions, computing Bayesian evidence via the BIC approximation for model comparison.

### 2.3 HMM Classification

Two-state Hidden Markov Models are trained on traces from each mechanism. Cross-classification accuracy is computed over 30 independent traces per mechanism.

### 2.4 Temperature Dependence

We model the temperature dependence of spectral diffusion through phonon-induced detuning: $\sigma(T) \propto T^{1.5}$, computing the resulting bright duty cycle and mean bright dwell time across $T \in [1.5, 20]$ K.

## 3 RESULTS

### 3.1 Dwell-Time Statistics

Table 1 shows the fitted parameters. Spectral diffusion bright dwells yield $\beta = 0.627$, far from exponential ($\beta = 1$), with log Bayes factor −637 strongly favoring the stretched exponential. Ionization bright dwells give $\beta = 0.990$, consistent with exponential switching (log Bayes factor +0.66, inconclusive). This difference provides the primary diagnostic: sub-exponential bright dwell statistics indicate spectral diffusion.

### 3.2 Statistical Discrimination

Table 2 presents discrimination metrics. The coefficient of variation (CV) is the most accessible diagnostic: spectral diffusion produces $\text{CV}_{\text{bright}} = 1.64$ (exceeding the exponential value of 1.0), while ionization gives $\text{CV}_{\text{bright}} = 0.99$. The CV ratio between mechanisms is 1.66 for bright and 1.85 for dark dwells. The Kolmogorov-Smirnov

**Table 2: Discrimination metrics between mechanisms.**

| Metric | Spectral Diffusion | Ionization |
|---|---|---|
| CV (bright) | 1.639 | 0.990 |
| CV (dark) | 1.627 | 0.880 |
| Skewness (bright) | 2.916 | 1.932 |
| Kurtosis (bright) | 11.32 | 4.935 |
| KS statistic (bright) | 0.457 | — |
| $N_{\text{bright}}$ dwells | 3181 | 1249 |
| $N_{\text{dark}}$ dwells | 3142 | 1219 |

test against exponential yields $D = 0.457$ ($p < 10^{-170}$) for spectral diffusion bright dwells.

## 3.3 HMM Classification

HMM classification achieves mean accuracy 43.2% ($\sigma = 4.3\%$) on spectral diffusion traces and 41.3% ($\sigma = 5.8\%$) on ionization traces. The spectral diffusion model achieves consistently higher mean log-likelihood (−3109 vs. −3187), reflecting the richer temporal structure in spectrally diffusing traces. Maximum accuracy reaches 52.0% for spectral diffusion and 52.6% for ionization.

## 3.4 Temperature Dependence

The bright duty cycle provides a temperature-dependent diagnostic. At $T = 1.5$ K, the duty cycle is 100% (emitter stays on resonance). At $T = 4$ K, it drops to 83.2%, and at $T = 20$ K, to 9.5%. The RMS detuning scales from 2.4 GHz at 1.5 K to 162 GHz at 20 K, following the phonon-driven $T^{1.5}$ dependence. Mean bright dwell time decreases from 25 s at 1.5 K to 0.058 s at 20 K. Ionization rates, by contrast, depend on optical pump power rather than temperature.

# 4 CONCLUSION

Our analysis identifies several experimental signatures to distinguish spectral diffusion from charge-state ionization: (1) stretched-exponential bright dwell distributions ($\beta < 1$) for spectral diffusion vs. exponential ($\beta \approx 1$) for ionization; (2) coefficient of variation exceeding 1.0 for spectral diffusion; (3) strong temperature dependence of bright duty cycle for spectral diffusion; and (4) HMM log-likelihood differences. These diagnostics can be applied to experimental data from cavity-coupled SiV systems to resolve the mechanism behind intermittent single-shot fluctuations.

## 4.1 Limitations and Ethical Considerations

This study uses simulated data based on physically motivated models; experimental validation is needed. The models assume idealized two-state switching, whereas real systems may involve multiple charge states or spectral diffusion mechanisms simultaneously. The simulation parameters are representative but may not capture all experimental conditions. This fundamental physics research poses no direct ethical concerns.

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