Testing the Temporal Structure of Single-Photon Emission with Trapped Ions

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Revision 2

Abstract

Spontaneous emission is one of the best-tested phenomena in quantum physics, with ensemble lifetimes confirmed to follow exponential decay laws to high precision. However, ensemble measurements probe only the statistics of *when* emission occurs, not the detailed temporal profile of the emitted photon itself. Standard QED assumes that the photon wavepacket follows the same exponential law as the excited-state population. Alternative models, including the recently proposed Vacuum Breathing Theory (VBT) [2], predict that each photon emerges as a finite, causally delayed wavepacket whose shape and width scale with experimental parameters.

This note outlines a feasible laboratory test using a single trapped ion, chirped excitation across resonance, and time-correlated single-photon counting (TCSPC). The experiment is designed to distinguish between a memoryless exponential envelope and a deterministic delayed wavepacket, with three falsifiable signatures: (1) a systematic positive lag relative to the resonance crossing, (2) scaling of the delay with $\Omega/|\alpha|$, and (3) mirrored wavepacket shapes under chirp reversal. Because the experiment uses only standard AMO techniques, it is achievable with existing university hardware. A positive result would motivate re-examination of spontaneous emission at the single-photon level, while a null result would place tighter bounds on non-exponential effects. In either case, the outcome is scientifically valuable.

1 Motivation

In quantum electrodynamics (QED), spontaneous emission is modeled as a memoryless process: the excited-state population decays exponentially, and photon emission times are probabilistically distributed as $P(t) = e^{-t/\tau}$. Ensemble lifetime measurements confirm this law to high precision.

The VBT framework, in contrast, models orbital transitions as *continuous re-locking events* to the Planck-frequency carrier. Photon emission is predicted to have a finite envelope that peaks *after* the programmed resonance crossing t_0, with a causal delay Δt. This difference does not contradict ensemble exponentials, but it makes a sharper prediction for the temporal mode of individual photons.

2 Predictions and Experimental Signature

The distinguishing signatures are:

1. **Positive causal lag:** Photon envelope peaks after t_0, i.e. $t_{\text{peak}} - t_0 \equiv \Delta t > 0$.

2. **Scaling:** Δt and the envelope width both scale as

$$\Delta t \propto \frac{\Omega}{|\alpha|},$$

where Ω is the Rabi rate and α is the chirp rate of the detuning.

3. **Chirp reversal:** Reversing the chirp sign ($\alpha \to -\alpha$) mirrors the photon envelope about t_0, providing a strong control.

Thus the experiment is not simply "looking for non-exponential behavior," but for a *specific, causal, and tunable signature* distinct from QED.

3 Proposed System: Ca^+ Single Ion

We consider the 397 nm $P_{1/2} \to S_{1/2}$ transition in Ca^+, with lifetime $\tau \approx 7$ ns. A chirped laser sweeps across resonance with slope α, defining t_0. The Rabi frequency Ω is set by laser intensity.

Expected delays:

$\Omega/2\pi$ (MHz)	$\alpha/2\pi$ (MHz/ns)	Ω/α (ns)	Δt (ns)	Regime
10	5.0	20	$\sim$2	Fast
20	1.0	400	$\sim$20	Moderate
30	0.2	4500	$\sim$150	Adiabatic

All values are comfortably above detector resolution ($\sim$50 ps). Histograms with 10^6 counts can be acquired in a few hours at typical ion count rates (50–200 cps).

4 TCSPC Implementation

To resolve Δt, we adopt established TCSPC best practice [1]:

Single-photon regime. Keep count rates below 1–5% of repetition rate to avoid pile-up bias, using filtering or reduced NA as needed.

Instrument response function (IRF). Measure the IRF at the emission wavelength and fit by iterative reconvolution. This allows recovery of temporal features below the IRF FWHM.

Timing architecture. Operate in forward start–stop mode with time-tagged time-resolved (TTTR) acquisition. Both chirp trigger and photon arrivals are recorded on the same clock, fixing t_0 per shot.

Dead time and pile-up. Use low-dead-time detectors (SNSPDs or fast PMTs) and verify Δt independence with power-down scans.

Resolution. With 30–50 ps detector timing and calibrated chirp triggers, delays as small as 1–2 ns are resolvable.

5 Expected Outcome

QED predicts that spontaneous emission is strictly memoryless: each photon emerges with an exponential temporal distribution, characterized solely by the natural lifetime of the transition. In this framework there is no deterministic onset delay, no modulation of instantaneous frequency, and no scaling law beyond the exponential decay constant.

In contrast, the Vacuum Breathing Theory (VBT) makes three distinct predictions, each accessible to single-photon time-correlated measurements:

1. **Finite emission envelope.** Rather than an unbounded exponential, VBT predicts a photon packet of finite duration with a causal onset delay Δt following excitation, as shown in Fig. 1.

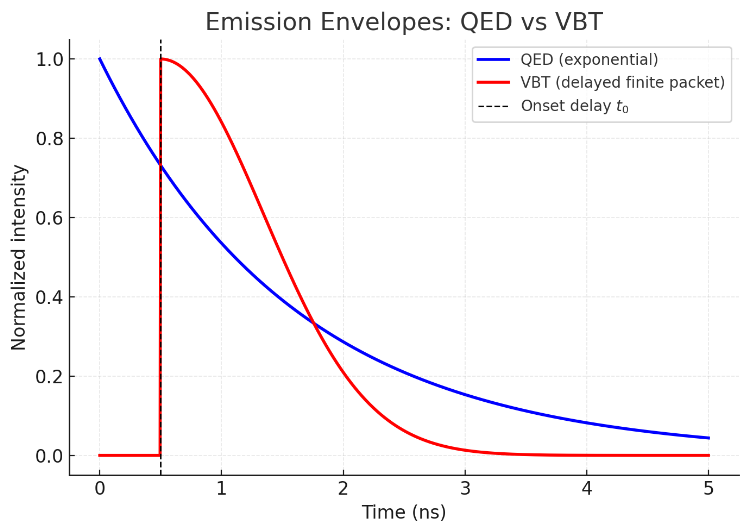

Figure 1: **Emission envelopes.** QED yields a purely exponential decay with no onset delay. VBT predicts a finite photon packet with a causal onset at t_0. Both curves are normalized.

2. **Frequency chirp reversal.** As the electron re-locks to the vacuum breathing mode, VBT predicts a sweep of instantaneous frequency (chirp). The sign of this chirp depends on the coupling parameter α: positive α yields an up-chirp, while negative α yields a mirrored down-chirp (Fig. 2).

3. **Scaling law for delay.** The onset delay Δt scales linearly with the coupling ratio $\Omega/|\alpha|$, providing a quantitative benchmark for falsifiability. This scaling is shown in Fig. 3.

Together, these outcomes provide a sharp experimental contrast. QED expects only exponential decay, with no delay, no chirp, and no scaling beyond the lifetime constant. VBT predicts a delayed finite packet, a chirp reversal, and a tunable onset scaling. Importantly, either outcome is valuable: confirmation of QED at single-photon resolution would further validate its scope, while observation of any VBT signature would constitute direct evidence for deterministic re-locking dynamics.

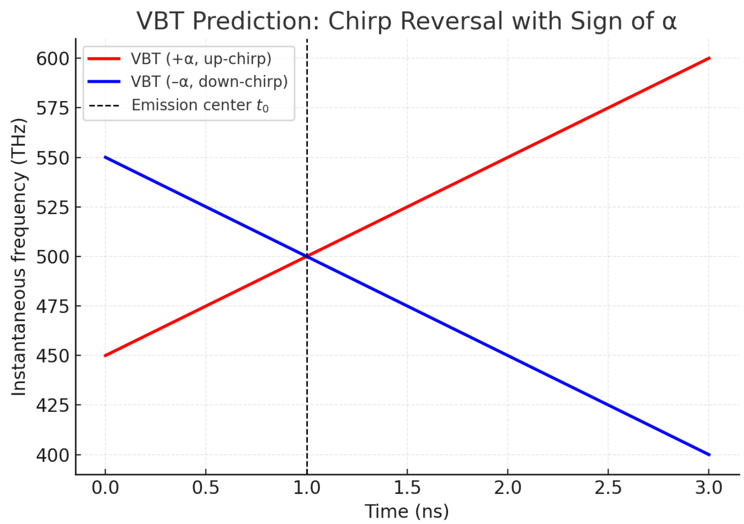

Figure 2: **Chirp reversal.** VBT predicts an instantaneous frequency sweep whose sign depends on α. QED has no mechanism for such reversal.

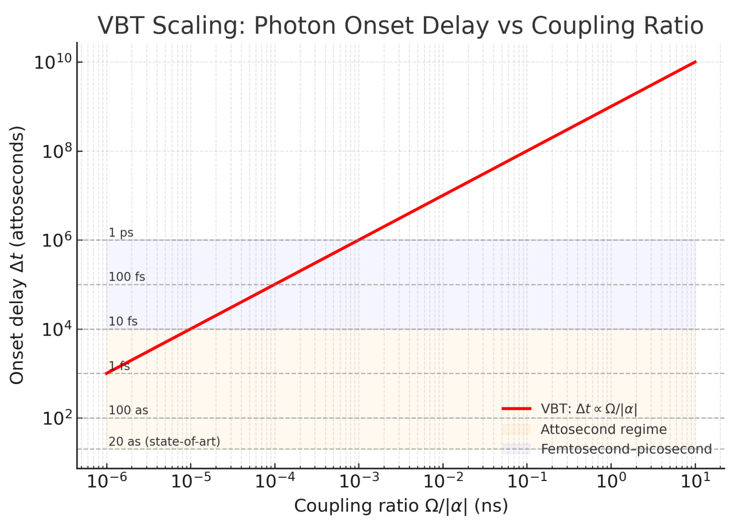

Figure 3: **Scaling of photon onset delay.** VBT predicts a deterministic delay Δt proportional to $\Omega/|\alpha|$, plotted here in physical units (attoseconds). Experimental timing benchmarks are overlaid. QED predicts $\Delta t = 0$.

6 Conclusion

This experiment is feasible with existing university AMO hardware. Because it builds directly on established TCSPC practice, it requires no new technology—only a new framing of the measurement. A positive result would provide direct evidence for the VBT re-locking mechanism, while a null result would reinforce the conventional QED picture.

References

[1] Becker & Hickl GmbH. *Time-Correlated Single Photon Counting: Principles and Applications*, Technical Note, 2023. Available at: `https://www.becker-hickl.com/`.

[2] D. Poole, *Vacuum Breathing Theory: A Deterministic Framework for Atomic and Cosmological Phenomena*, Zenodo, 2025. doi: 10.5281/zenodo.17050452.