Superradient decay of nonlinearly excited electric dipole spin waves in a cold atomic gas

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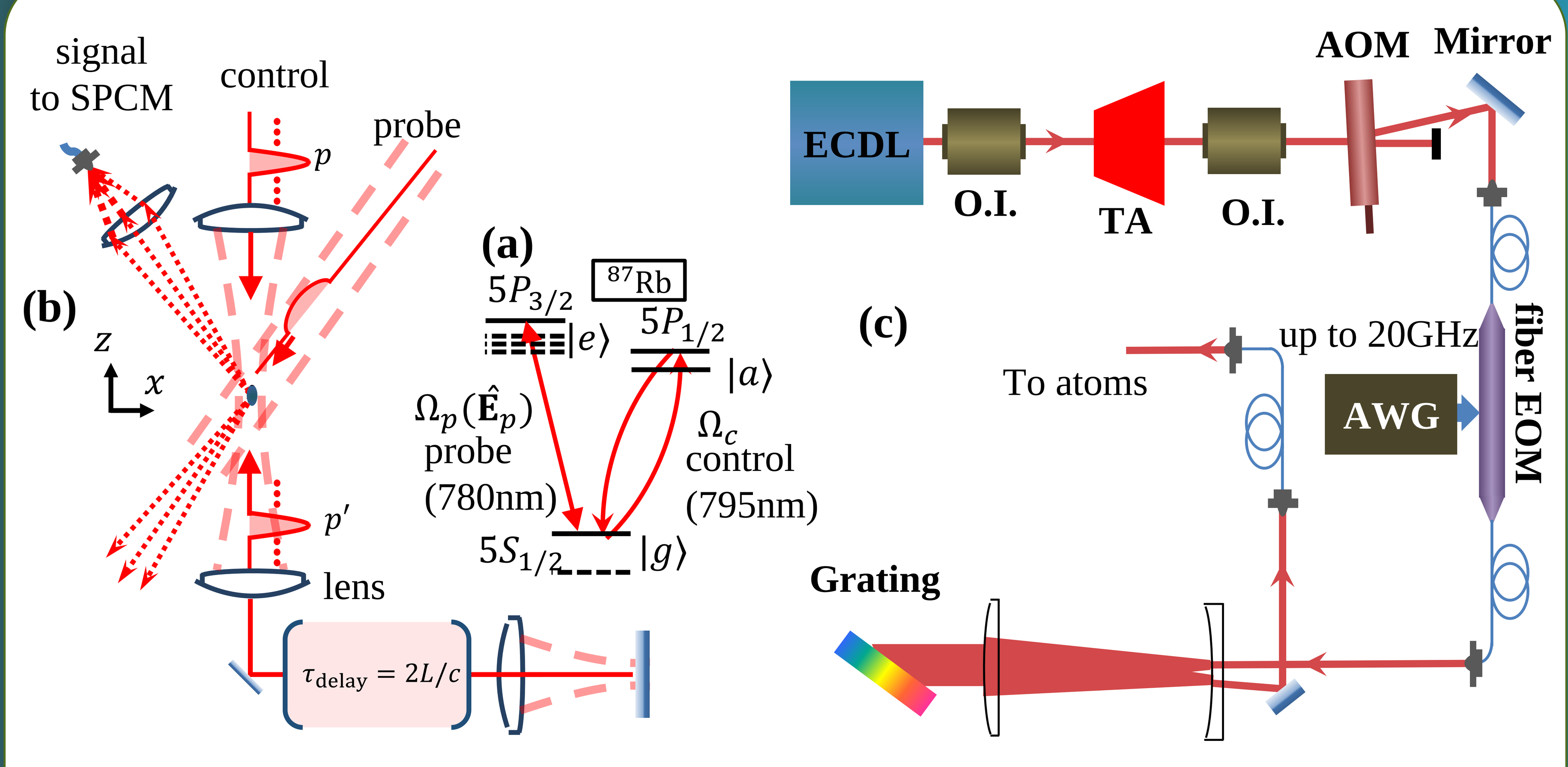
Introduction

When a dense cloud of ultracold atoms is excited strongly by an optical pulse, the phased collective emission in the forward direction is overall superradiant, similar to the superradience in the linear optics regime. However, unlike dynamics of weakly excited spin waves that can largely be described classically, the dynamics of the nonlinearly excited spin waves is defined in an exponentially large Hilbert space, subjected to long-range electric dipole interactions, and is often prohibitively difficult to simulate classically. Therefore, superradience of nonlinearly excited dipole spin waves is arguably more intriguing to understand than those associated with the timed-Dicke single-photon excitations. Equipped with a wideband optical waveform generator, we temporally shift the wavevector of the strongly excited dipole spin-waves in a Rb87 cloud to separate the collective forward emission from the much stronger excitation pulse itself. The technique allows us to precisely measure the collective emission dynamics deeply in the nonlinear excitation regime, for the first time to our knowledge. We find that before the superradience occur, there is a period when the decay of the nonlinearly excited spin wave order is much slower, a phenomena agreeable with the mean-field theory in e.g., standard nonlinear optics. Quantitatively, however, the measured decay curves deviate substantially from the simple theories that ignore the many-body, multi-level correlations.

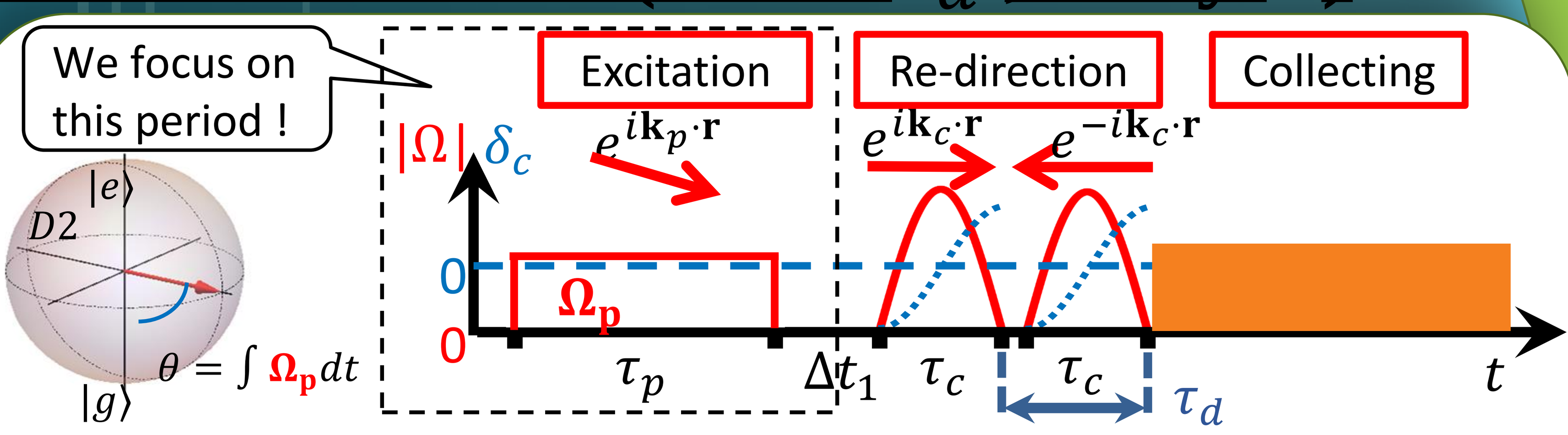
Experimental Setup

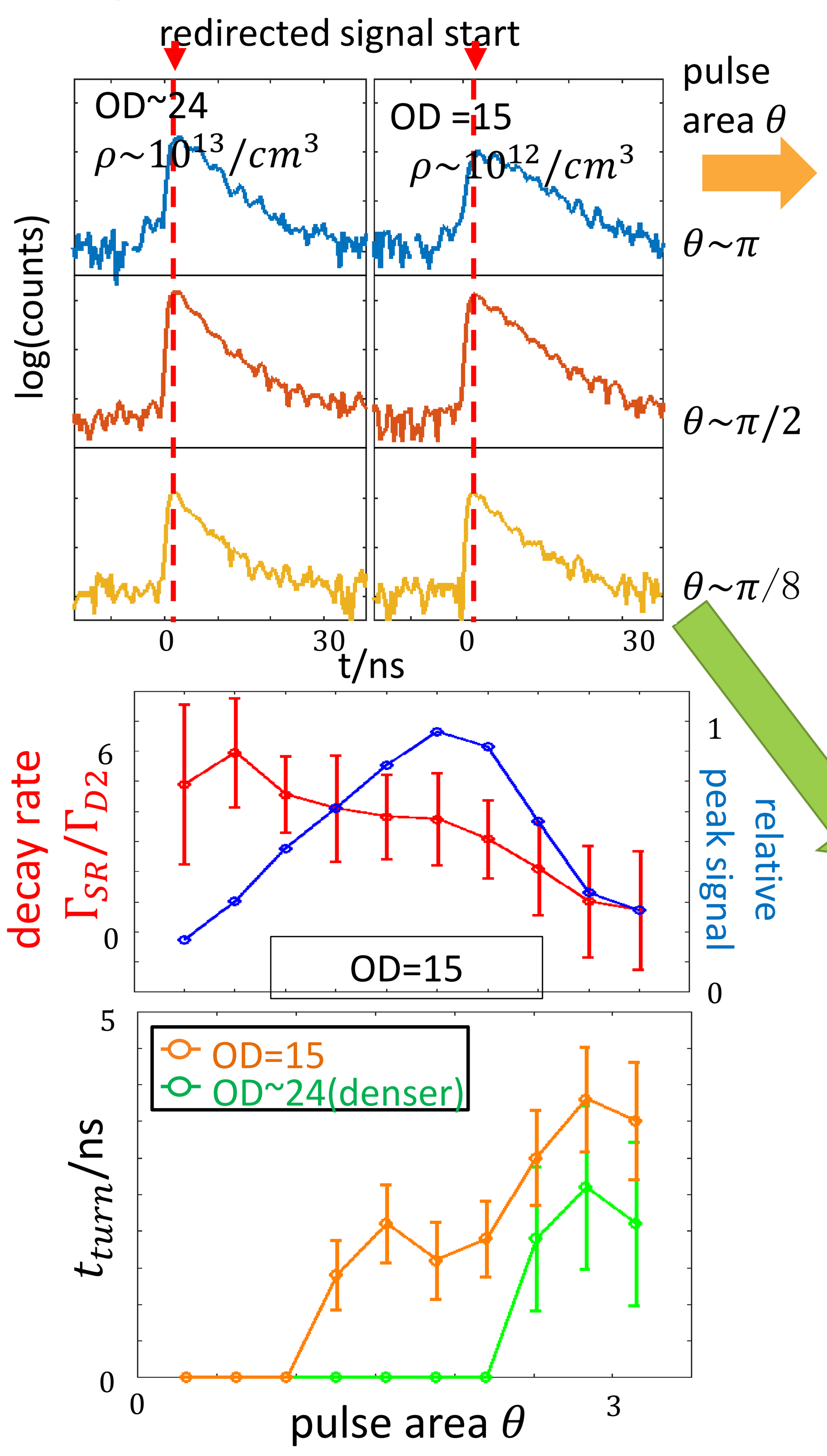


Experiment A:
Measuring strongly excited D2 dipole spin wave decay with BK-free superradience readouts.

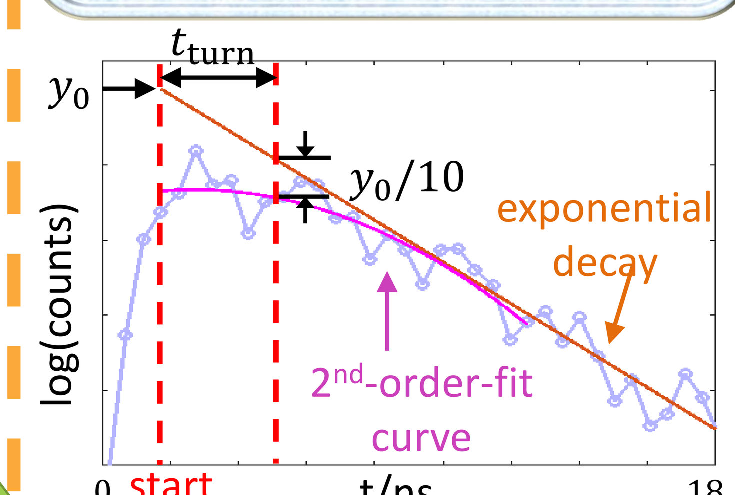
Experiment B:
Monitoring the dynamics of fully inverted D1 gas, with spin-wave encoded as $5P_{1/2}$-$5P_{3/2}$ coherence to be readout later.

D2 observation (small τ_d, Vary θ)



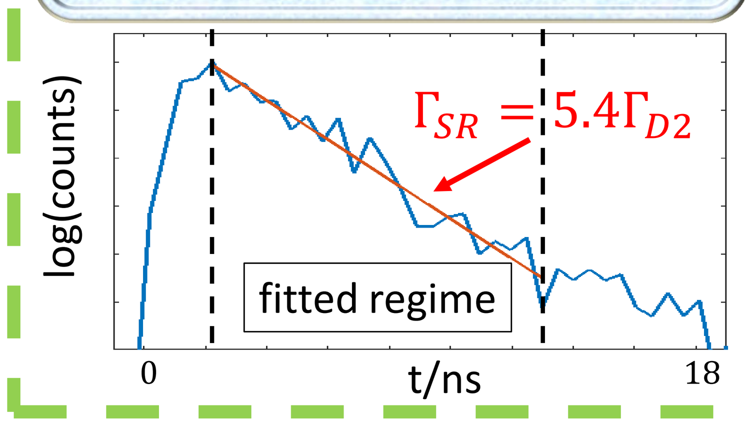


We fit the latter data with linear curve A and initial data with 2nd-order-fit curve B. The intercept of A and B at start is y_0. We find the time when the intercept decreases to y_0/e and define the time as turning point t_{turn}.

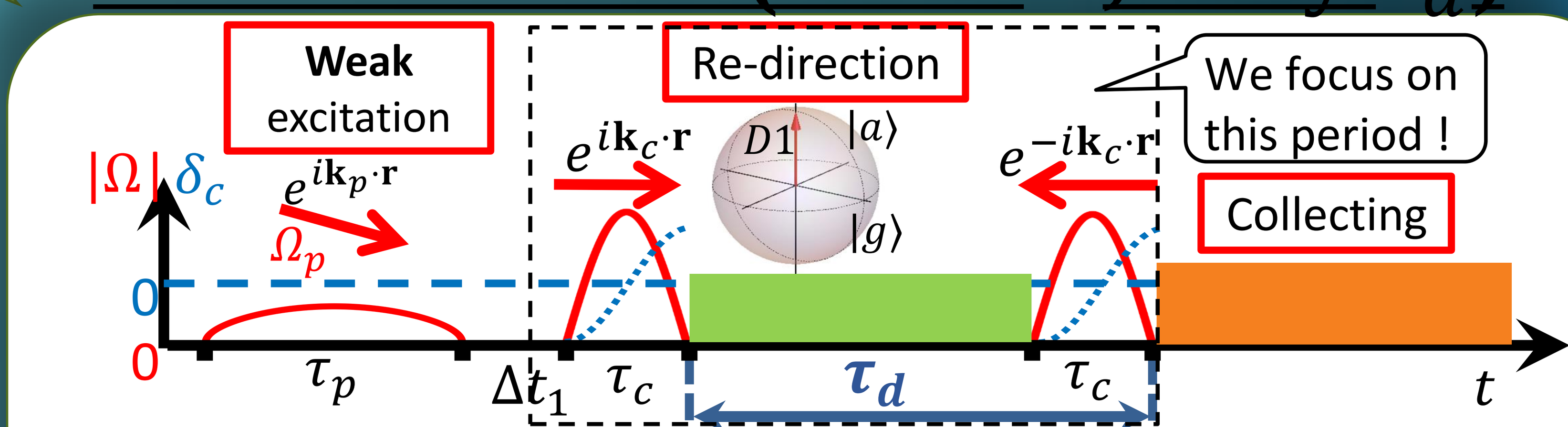


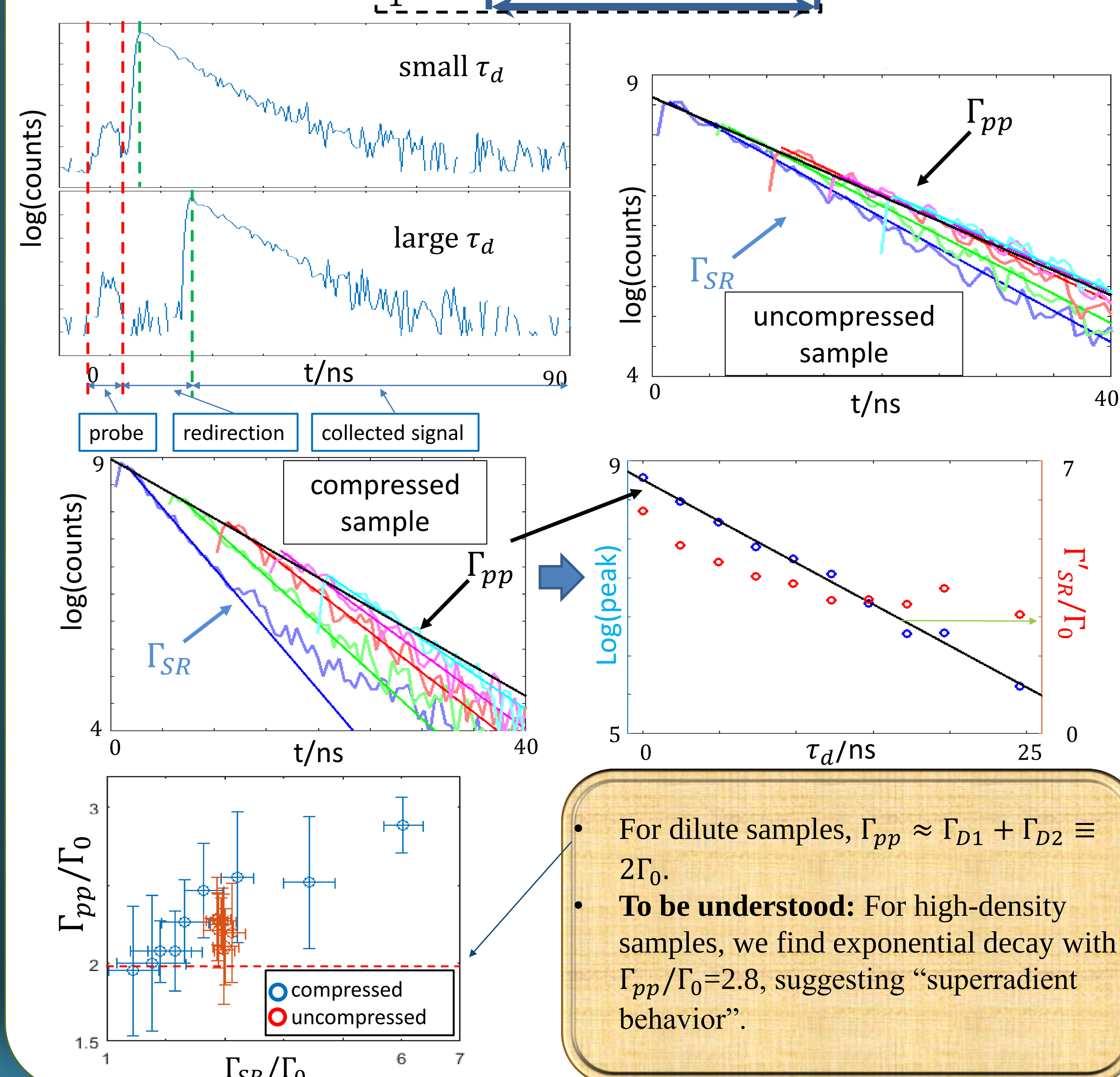
The initial decay rate Γ_{SR} in weak excitation regime monitors the optical depth (OD)[2]:

$$\Gamma_{SR} = (1 + 0.35\ \mathrm{OD})\Gamma_{D2}$$



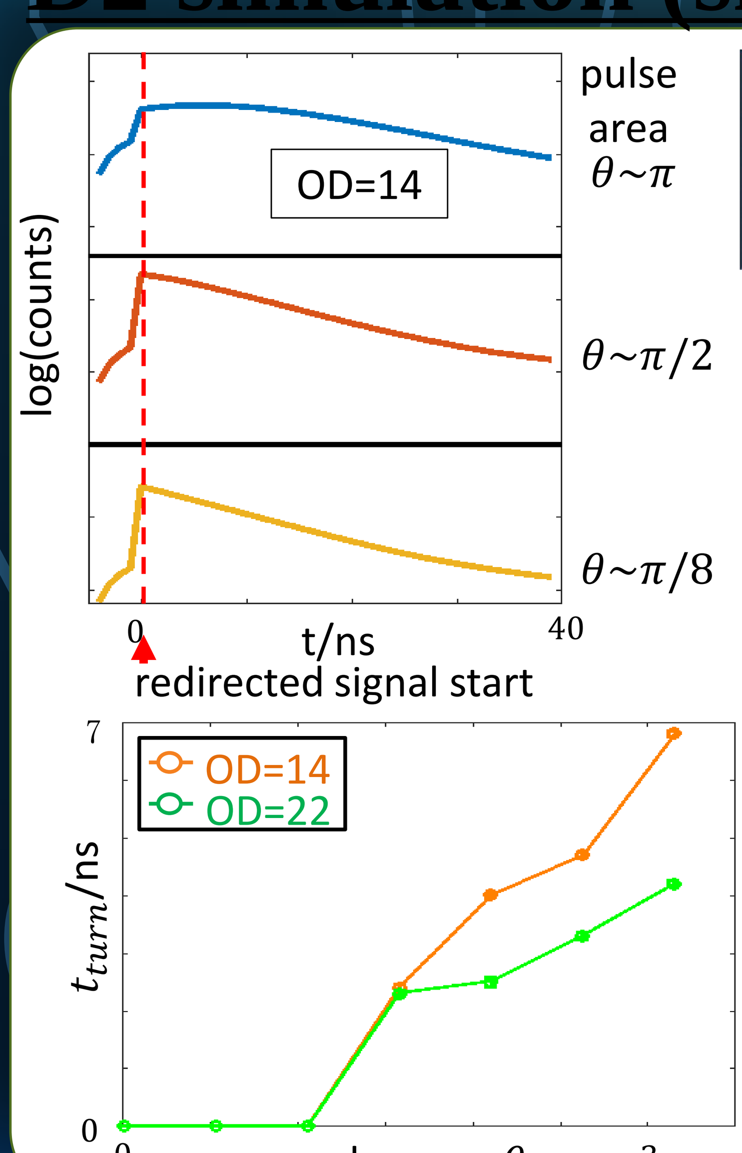
D1 observation (small θ, Vary τ_d)





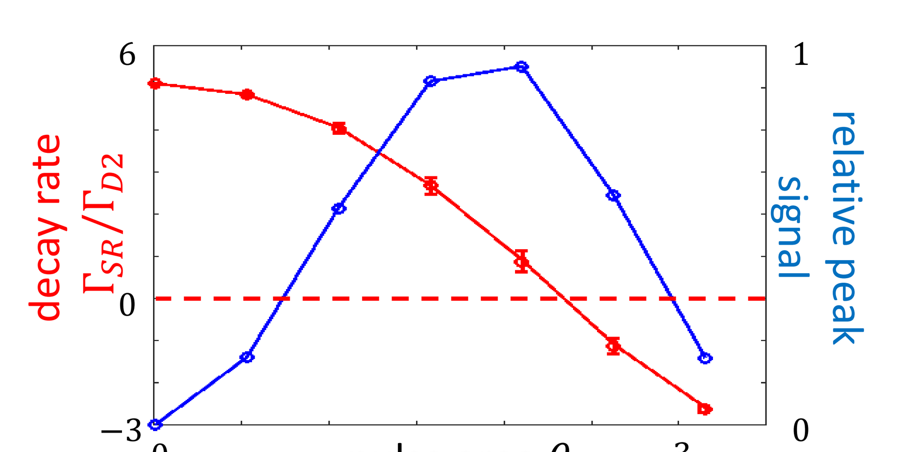
- For dilute samples, $\Gamma_{pp} \approx \Gamma_{D1} + \Gamma_{D2} \equiv 2\Gamma_0$.
- **To be understood:** For high-density samples, we find exponential decay with Γ_{pp}/Γ_0=2.8, suggesting "superradient behavior".

D2 simulation (small τ_d, Vary θ)



J=0 to J=1 transitions. Incident linear polarization.

Mean field approximation $\hat{\rho} = \hat{\rho}_1 \otimes \hat{\rho}_2 \otimes \cdots \otimes \hat{\rho}_n$



simulation VS experiment

Agreed: Nonlinearly excited spin waves decay much slower initially

Disagreed: No negative slop as in the simulation is found experimentally.

The experimentally observed nonlinear dynamics is generally faster.

Summary and outlook

- Equipped with electric-dipole spin wave control technique, we measure the superradient dynamics in cold atoms in the strong-excitation regime for the first time to our knowledge. The SR dynamics different quantitatively from the mean field theory. We are investigating the physics behind the discrepancy.
- By delaying the population transfer from $P_{1/2}$ state back, we measure the fine-structure coherence decay during the spin-wave geometric control, also for the first time to our knowledge. The $P_{1/2}$-$P_{3/2}$ coherence decay behaves as $\Gamma_{pp} \approx \left(2 + \frac{OD}{12}\right)\Gamma_0$, contradict our expectation based on short-range P-P interaction.

Reference

- [1] Y. He, L. Ji, et al, *"Geometric control of collective spontaneous emission"*. Phys. Rev. Lett., **125**, 213602(2020).
- [2] Y. He, L. Ji, et al, *"Atomic spin-wave control and spin-dependent kicks with shaped subnanosecond pulses"*. Phys. Rev. Research, **2**, 043418(2020)
- [3] S. L. Bromley, B. Zhu, M. Bishof, et al. *"Collective atomic scattering and motional effects in a dense coherent medium"*. Nat. Commun. 7, 11039 (2016).

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