Observation of vacuum-induced collective quantum beats

Huan Q. Bui

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Observation of vacuum-induced collective quantum beats

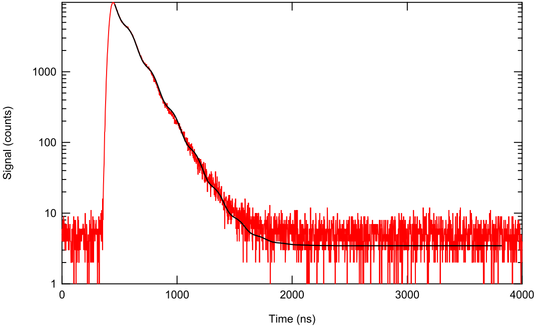
Hyok Sang Han,[1] Ahreum Lee,[1] Kanupriya Sinha,[2,*] Fredrik K. Fatemi,[3,4] and S. L. Rolston[1,4,†]

[1] *Joint Quantum Institute, University of Maryland and the National Institute of Standards and Technology, College Park, Maryland 20742, USA*
[2] *Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*
[3] *U.S. Army Research Laboratory, Adelphi, Maryland 20783, USA*
[4] *Quantum Technology Center, University of Maryland, College Park, MD 20742, USA*

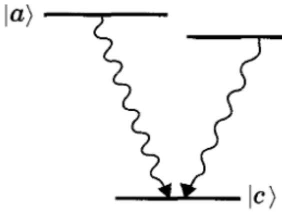
We demonstrate collectively enhanced vacuum-induced quantum beat dynamics from a three-level V-type atomic system. Exciting a dilute atomic gas of magneto-optically trapped ^{85}Rb atoms with a weak drive resonant on one of the transitions, we observe the forward-scattered field after a sudden shut-off of the laser. The subsequent radiative dynamics, measured for various optical depths of the atomic cloud, exhibits superradiant decay rates, as well as collectively enhanced quantum beats. Our work is also the first experimental illustration of quantum beats arising from atoms initially prepared in a single excited level as a result of the vacuum-induced coupling between excited levels.

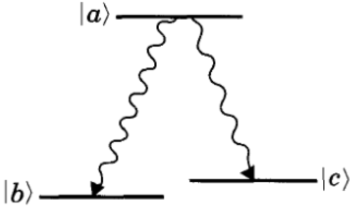
Quantum beats

- Oscillatory behavior in the intensity of radiation emitted by atomic/molecular systems in a superposition of (excited) states
- Ex: quantum beats in the decay $\left|5P_{3/2}\right\rangle \to \left|4S_{1/2}\right\rangle$ in ^{39}K



Simplest case is the three-level system. Two types: V and Λ.





$$|\psi_V(t)\rangle = \sum_{i=a,b,c} \alpha_i |i,0\rangle + \alpha_1 |c, 1_{\nu_1}\rangle + \alpha_2 |c, 1_{\nu_2}\rangle$$

$$|\psi_\Lambda(t)\rangle = \sum_{i=a,b,c} \alpha'_i |i,0\rangle + \alpha'_1 |b, 1_{\nu_1}\rangle + \alpha'_2 |c, 1_{\nu_2}\rangle$$

With

$$E_j^{(-)}(t) \sim a_j^\dagger e^{i\nu_j t} \quad \text{and} \quad E_j^{(+)}(t) \sim a_j e^{-i\nu_j t}$$

Beat note term:

$$\langle \psi_V(t)| \, E_1^{(-)}(t) E_2^{(+)}(t) \, |\psi_V(t)\rangle \sim \langle 1_{\nu_1} 0_{\nu_2}| \, a_1^\dagger a_2 \, |0_{\nu_1} 1_{\nu_2}\rangle \, e^{i(\nu_1 - \nu_2)t} \underbrace{\langle c|c\rangle}_{1}$$

$$\langle \psi_\Lambda(t)| \, E_1^{(-)}(t) E_2^{(+)}(t) \, |\psi_\Lambda(t)\rangle \sim \langle 1_{\nu_1} 0_{\nu_2}| \, a_1^\dagger a_2 \, |0_{\nu_1} 1_{\nu_2}\rangle \, e^{i(\nu_1 - \nu_2)t} \underbrace{\langle c|b\rangle}_{0}$$

- Quantum beats exist in V-type systems in general, but not in Λ-type.
- Side note: This is not explained by semi-classical theory.

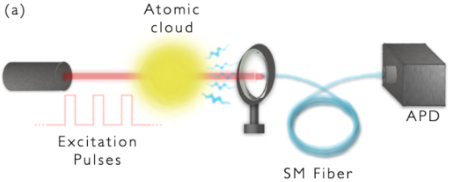
Textbooks: Quantum beats require a coherent superposition initially

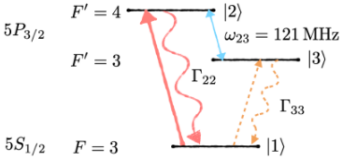
"Observation of..." by Han et al.

Experimentally demonstrates 2 new aspects:

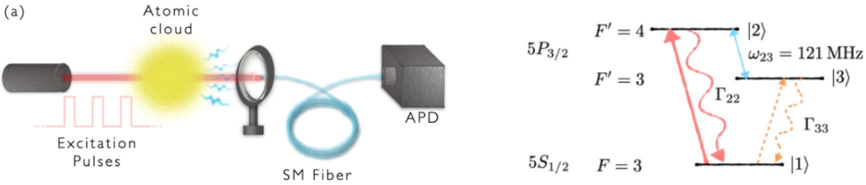
- **Vacuum-induced quantum beats:** observed quantum beats without an initial superposition of excited levels
- **Collective effect:** enhanced beat amplitudes

Experiment



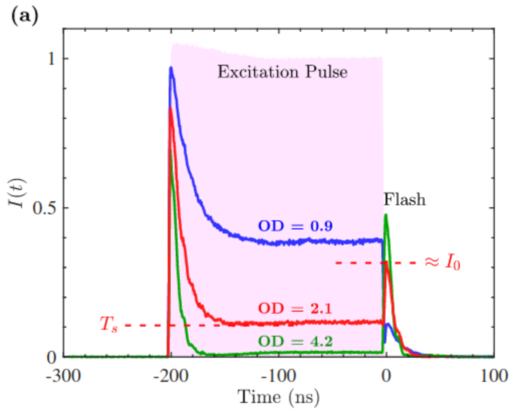


- $\sim 10^8$ ^{85}Rb atoms in a MOT, $\rho\lambda^3 \ll 1$
- V-type system, well-separated. $\Gamma_{22} = 2\pi \cdot 6.1$ MHz, $\Gamma_{33} = 5/9\Gamma_{22}$
- $\Gamma_{23} \approx \sqrt{\Gamma_{22}\Gamma_{33}}$: 2nd order coupling between $|2\rangle, |3\rangle$
- $v = 120$ nm/μs $\implies$ negligible to 780 nm over $1/\Gamma_{22} \approx 26$ ns



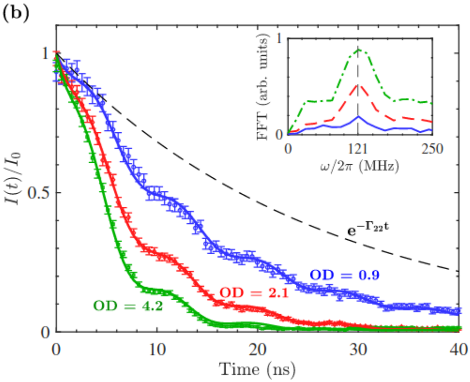
- Lin. pol. 780 nm light (D_2) drives $|1\rangle \to |2\rangle$. 200 ns on, 800 ns off.
- $>$ 30 dB extinction ratio (2 EOMs in series), 3.5 ns fall time.
- $I_x \ll I_s = 3.9$ mW/cm^2 $\implies$ single-excitation in $|2\rangle$
- Forward-photons collected by SM fiber into APD $\implies$ filters out incoherent fluorescence
- Histograms for $\sim$30 mins, new shot every 2 ms $\implies$ 2×10^8 shots

Data



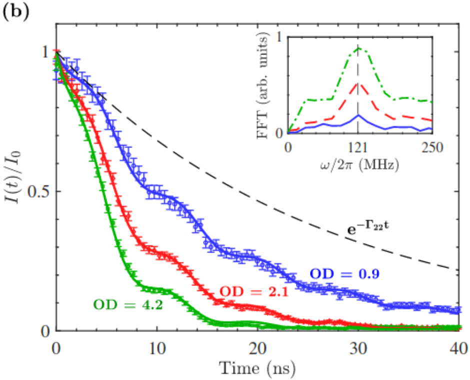
(a)
Excitation Pulse
Flash
OD = 0.9
OD = 2.1
OD = 4.2
$\approx I_0$
T_s
$I(t)$
1
0.5
0
-300
-200
-100
0
100
Time (ns)

Data



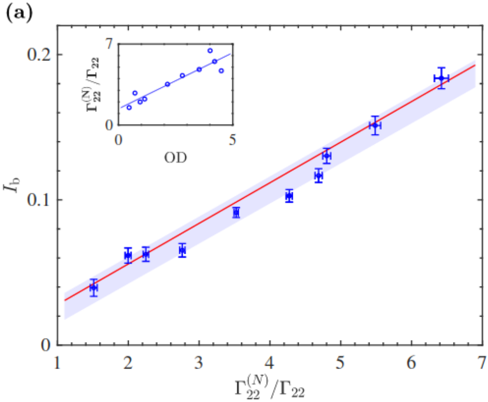
$$\frac{I(t)}{I_0} = e^{-\Gamma_{22}^{(N)}t} + I_b e^{-\Gamma_{\text{avg}}^{(N)}t} \sin(\omega_{23}t + \phi)$$

Data



(b)
$I(t)/I_0$
1
0.5
0
0
10
20
30
40
Time (ns)
$e^{-\Gamma_{22}t}$
OD = 0.9
OD = 2.1
OD = 4.2
FFT (arb. units)
1
0
0
121
250
$\omega/2\pi$ (MHz)

Data



(a)
0.2
0.1
0
I_b
1
2
3
4
5
6
7
$\Gamma_{22}^{(N)}/\Gamma_{22}$
7
0
0
5
OD
$\Gamma_{22}^{(N)}/\Gamma_{22}$

Model

$$\mathcal{H}$$

Model vs. Data

Conclusion

Summary:

- Demonstrated collective quantum beats in spontaneous emission process without initial superposition of excited states
- Observed
  - enhanced decay rates ("superradiance")
  - enhanced quantum beat amplitudes as a function of OD

  Good agreement with theoretical model and previous studies.

Applications:

- Tool in precision spectroscopy: enhancing signals
- Combined with waveguide optics to study interactions between distant atomic ensembles (e.g. ONF experiment at JQI)

References