Subradiance via entanglement in atoms with several independent decay channels

Laurin Ostermann
Martin Hebenstreit, Barbara Kraus, Helmut Ritsch

Institute for Theoretical Physics
University of Innsbruck
Technikerstraße 21/3, A-6020 Innsbruck
Outline

• Multilevel Dark States
• Mathematical Properties
• Preparation
Spontaneous Emission

\[ |e\rangle \]

\[ |g_1\rangle \]

\[ \Gamma = \frac{\omega^3 \mu^2}{3\pi \varepsilon_0 c^3} \]
Two Atoms
Two Atoms
Two Atoms

No dark state is known.
\[
\dot{\rho} = i [\rho, H] + \mathcal{L} [\rho]
\]

\[
H = \sum_{i,j} -\omega_j^i \sigma_j^i - \sigma_j^i + \sum_{i \neq k} \sum_{j} \Omega_j^{ik} \sigma_j^i + \sigma_j^k
\]

\[
\mathcal{L}[\rho] = \frac{1}{2} \sum_{i,k,j} \Gamma_{ij}^{ik} \left[ 2\sigma_j^i - \rho \sigma_j^k + - \sigma_j^i + \sigma_j^k - \rho - \rho \sigma_j^i + \sigma_j^k \right]
\]
\[ |\psi_d^3\rangle = \frac{1}{\sqrt{6}} \left\{ |e g_1 g_2\rangle + |g_1 g_2 e\rangle + |g_2 e g_1\rangle - |e g_2 g_1\rangle - |g_2 g_1 e\rangle - |g_1 e g_2\rangle \right\} \]
Generalization

$$|\psi_d^N\rangle = \frac{1}{\sqrt{N!}} \sum_{\pi \in S_N} \text{sgn}(\pi) \bigotimes_i |s_{\pi(i)}\rangle$$

$$|0\rangle = |s_0\rangle = |e\rangle$$
$$|i\rangle = |s_i\rangle = |g_i\rangle$$
Math. Properties

• Dipole moments vanish

\[ \langle \mu_j \rangle = 0 \]

• Bipartite entanglement is maximal

\[ \rho_1 \propto 1 \]

• No individual information: Subradiance is purely non-classical and non-local
Math. Properties

• Invariant under any invertible single-atom operator

\[ |\psi_d^N \rangle \propto S^{\otimes N} |\psi_d^N \rangle \]

\[ \rightarrow \text{announce measurement, create} \]

\[ |\psi_d^{N-1} \rangle \]

deterministically by LUs only
Preparation

- Deterministically (3 atoms)

\[
\frac{1}{\sqrt{2}} (|01\rangle - |10\rangle) \otimes |2\rangle
\]

\[
\exp \left( -i \frac{2\pi}{9} (X \otimes X \otimes X + \text{h.c.}) \right)
\]

\[
X = |1\rangle \langle 0| + |2\rangle \langle 1| + |0\rangle \langle 2|
\]
Preparation

- Probabilistically (3 atoms)

\[ |\psi_1\rangle = \frac{1}{\sqrt{2}} (|eg_1\rangle - |g_1e\rangle) \otimes |g_2\rangle \]

\[ |\psi_2\rangle = \frac{1}{\sqrt{2}} (|eg_1\rangle - |g_1e\rangle) \otimes |g_1\rangle \]
Preparation

- Probabilistically (3 atoms)
Conclusions

• Subradiance persists for more than one decay channel per atom

• Anti-symmetric, highly entangled multi-partite states

• Deterministic & probabilistic preparation
QuantumOptics.jl

A Julia Framework for Open Quantum Dynamics

QuantumOptics.jl is a numerical framework written in the Julia programming language that makes it easy to simulate various kinds of open quantum systems. It is inspired by the Quantum Optics Toolbox for MATLAB and the Python framework QuTiP.

Performance
QuantumOptics.jl optimizes processor usage and memory consumption by relying on different ways to store and work with operators.

Usability
The framework comes with a plethora of pre-defined systems and interactions making it very easy to focus on the physics, not on the numerics.

Reliability
Every function in the framework has been severely tested with tests and their code coverage presented on the framework's GitHub page.
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