Lasers & Photons on Demand: Exploring the Atomic Applications of Strontium

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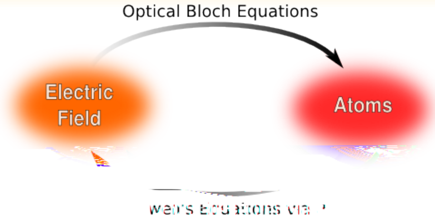
Why Strontium?

- Extremely long lifetime optical transition
- ${}^1S_0 - {}^3P_0$ transition is doubly forbidden
- Linewidth is extremely narrow (mHz vs. MHz)
- Used to drive atomic clock here at JILA

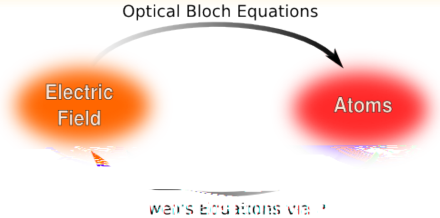
Basic Theory

- Atom - Field interactions



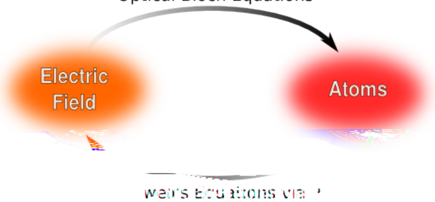
Basic Theory

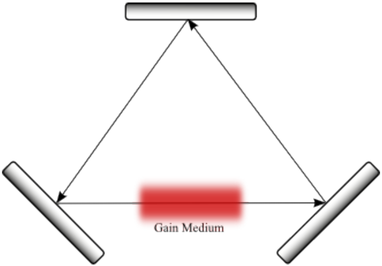
- Atom - Field interactions
- Coherence time



Basic Theory

- Atom - Field interactions
- Coherence time
- Ring laser





Describing the Atoms

- State vector for two-level atoms: $|\psi(t)\rangle = c_a(t)|a\rangle + c_b(t)|b\rangle$
- Density matrix

$$\rho = \begin{pmatrix} c_a c_a^* & c_a c_b^* \\ c_b c_a^* & c_b c_b^* \end{pmatrix} = \begin{pmatrix} \rho_{aa} & \rho_{ab} \\ \rho_{ba} & \rho_{bb} \end{pmatrix}$$

Density Matrix Equations of Motion

$$\begin{aligned} \dot{\rho}_{aa} &= W'\rho_{bb} - \gamma\rho_{aa} - \frac{i}{\hbar}V'_{ab}e^{i(\omega_0-\omega)t}\tilde{\rho}_{ba} + \frac{i}{\hbar}V'_{ba}e^{-i(\omega_0-\omega)t}\tilde{\rho}_{ab} \\ \dot{\rho}_{bb} &= -W'\rho_{bb} + \gamma\rho_{aa} + \frac{i}{\hbar}V'_{ab}e^{i(\omega_0-\omega)t}\tilde{\rho}_{ba} - \frac{i}{\hbar}V'_{ba}e^{-i(\omega_0-\omega)t}\tilde{\rho}_{ab} \\ \dot{\tilde{\rho}}_{ab} &= -\gamma_{ab}\tilde{\rho}_{ab} + \frac{i}{\hbar}e^{i(\omega_0-\omega)t}V'_{ab}(\rho_{aa} - \rho_{bb}) \end{aligned}$$

Describing the Light Field

- Start with a classical wave

$$E(z,t) = \frac{1}{2}\sum_n E_n(t) e^{-i(\omega_n t + \phi_n)} U_n(z) + c.c.$$

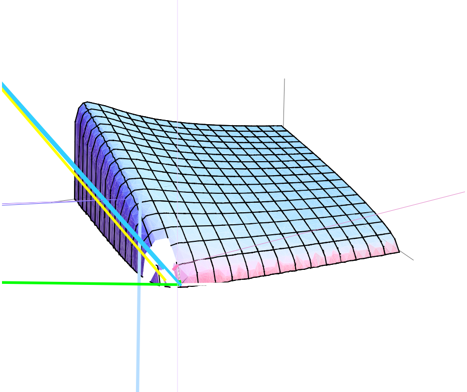
- After some math

Equation of Motion for Field

$$\dot{E}_n = -\frac{\omega}{2Q_n} E_n - \frac{\omega}{2\epsilon_o} \mathrm{Im}(2p e^{-i(kz + (\omega_0 - \omega)t)} \tilde{\rho}_{ab})$$

Adiabatically Eliminating the Field

- Field relaxes much faster than the atoms
- Set $\dot{E}_n = 0$ and find steady-state solution



A Promising Outlook

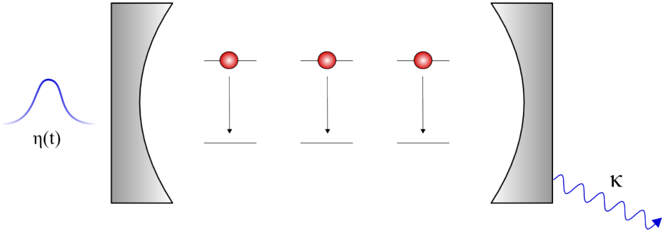
- Laser linewidth 16 orders of magnitude smaller than normal!
- Preliminary calculations show such a system is feasible
- Should be realizable with currently available technology
- Could be built in JILA in the near future

What Are Photons On Demand?

- Want an exact number of photons at a precisely determined time
- Applications in quantum networking and cryptography

Our Approach

- Atoms arranged in cavity
- On-resonant laser pulse triggers stimulated emission
- Photons decay out of cavity at rate κ



Hamiltonian Operator

Schrödinger Equation

$$\frac{\partial \psi}{\partial t} = \frac{1}{i\hbar} H\psi(t)$$

- Need to determine Hamiltonian for each individual component in the system.
  - Atoms H_a
  - Light field H_f
  - Interaction between atoms and field H_{a-f}
  - Pump laser $H_{pump}(t)$
- $H_{total}(t) = H_a + H_f + H_{a-f} + H_{pump}(t)$

The Density Matrix ρ

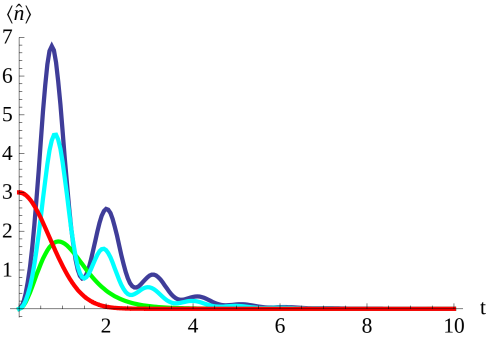
- Necessary to represent damping
- Impossible to know state vector ψ exactly
- Only know probabilities of states
- Density matrix used to represent this mixture

Master Equation

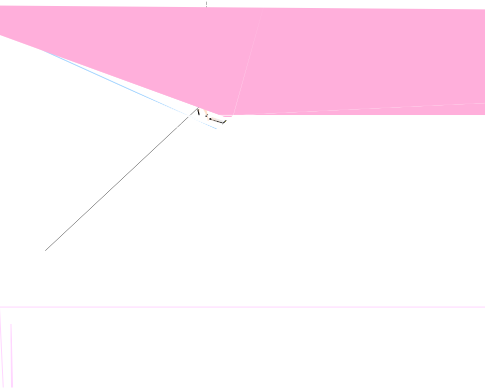
$$\begin{aligned}\frac{\partial \rho}{\partial t} &= \frac{1}{i\hbar}(H(t)\rho(t) - \rho(t)H(t)) \\ &\quad -\frac{\kappa}{2}(a^\dagger a\rho(t) + \rho(t)a^\dagger a - 2a\rho(t)a^\dagger)\end{aligned}$$

Time Evolution of Light Field

- With no atoms, pulse enters cavity and decays
- With atoms, pulse initiates large wave of photons into cavity
- Noise from pulse is negligible



Photon Probabilities



The Future

- Proof-of-concept results from both projects
- Further, more detailed simulations will be required
- Current technology should be sufficient to realize both systems

Acknowledgements

- Murray Holland
- Dominic Meiser