Monte Carlo Wave Functions To Model Doppler Laser Cooling

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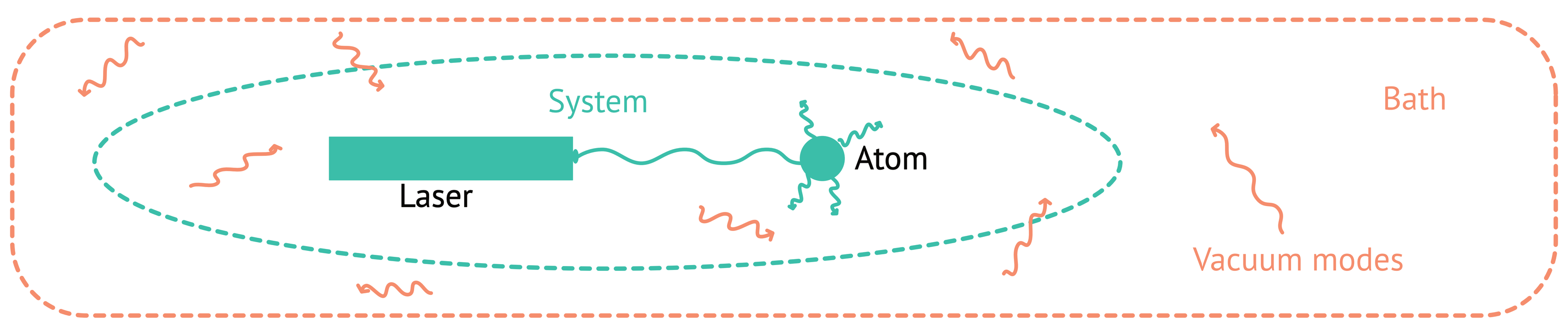
BACKGROUND

Abstract

Optical control and manipulation of atoms at the quantum level is at the heart of several atomic physics experiments. In this work, we model the evolution of electronic and motional states of an atom interacting with laser fields. We use a numerical approach known as Wave Function Monte Carlo simulations to model the dissipative interaction of the atom with the reservoir made of electromagnetic vacuum modes. We hope to use these techniques to develop a quantum description of some novel laser cooling techniques.

Spontaneous Emission



Spontaneous emission is the process by which atoms randomly emit photons into the vacuum modes of the quantized electric field. These photons transfer energy away from the system and into the bath irreversibly with a characteristic time scale. The energy transfer causes a quantum jump.

Time Evolution

Schrödinger Equation (Time Translation Operator)

$$|\psi(t+\delta t)\rangle = e^{\frac{-i\delta t H}{\hbar}}|\psi(t)\rangle$$

— No spontaneous emission
— Pure states only

Liouville Equation for Density Matrix

$$\dot{\rho}_s = \frac{i}{\hbar}[\rho_s, H]$$

— No spontaneous emission
— Mixed states allowed

Lindblad Master Equation

$$\dot{\rho}_s = \frac{i}{\hbar}[\rho_s, H] + \sum_m C_m \rho_s C_m^\dagger - \frac{1}{2}\sum_m (C_m^\dagger C_m \rho_s + \rho_s C_m^\dagger C_m)$$

— Spontaneous emission
— Mixed states
— SLOW

Monte Carlo Wave Functions

$$|\psi(t+\delta t)\rangle = \left(I + \frac{-i\delta t H}{\hbar}\right)|\psi(t)\rangle$$

$$H = H_s - \frac{i\hbar}{2}\sum_m C_m^\dagger C_m$$

— Spontaneous emission
— Mixed states
— FAST

Algorithm

Goal: model the time evolution of a system described by hamiltonian *H*.

repeat REPEAT

1. Initial wave function

$$|\psi(t)\rangle$$

2. Propagate by δt

$$|\psi(t+\delta t)\rangle = C_m|\psi(t)\rangle$$

Quantum jump

$$|\psi(t+\delta t)\rangle = \left(I + \frac{-i\delta t H}{\hbar}\right)|\psi(t)\rangle$$

Coherent Evolution

3. Normalize

$$|\psi(t+\delta t)\rangle = \frac{C_m|\psi(t)\rangle}{\sqrt{\langle\psi(t)|C_m^\dagger C_m|\psi(t)\rangle}}$$

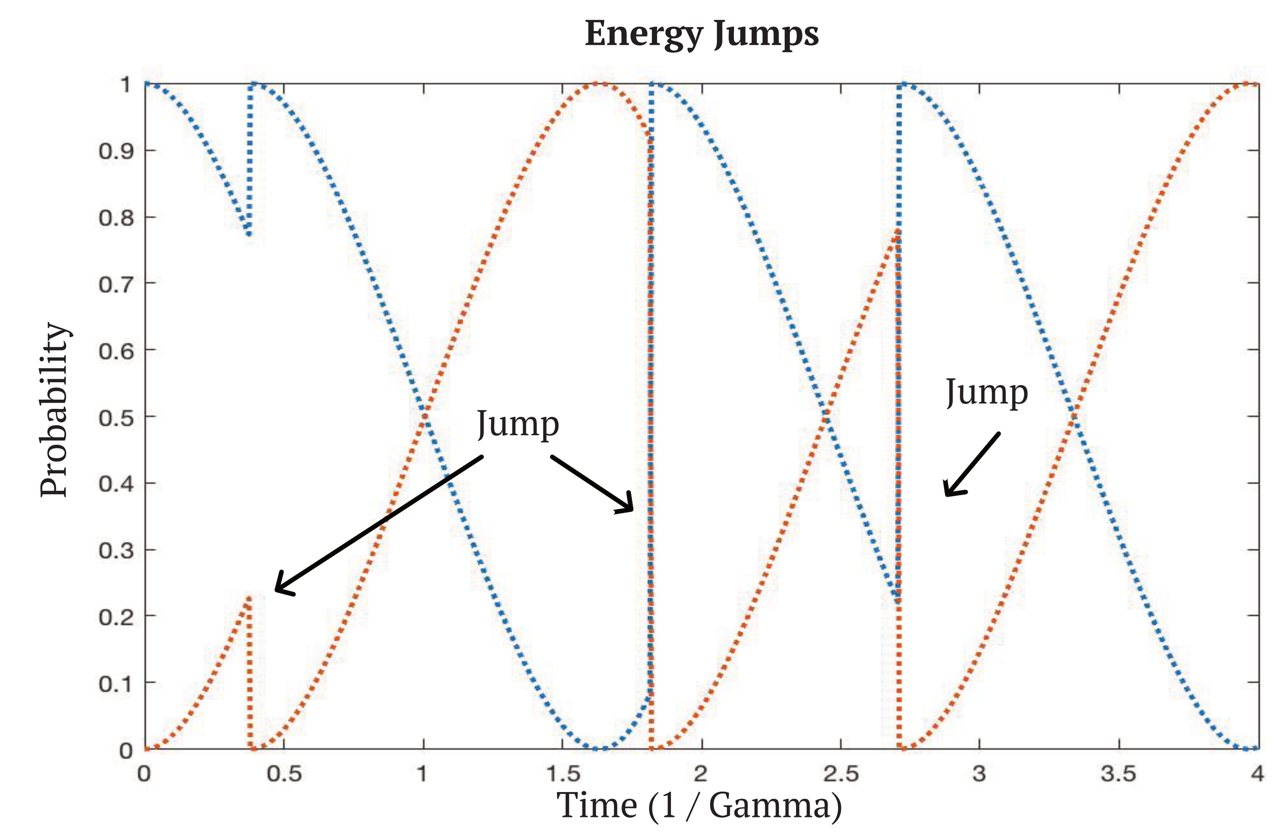
$$|\psi(t+\delta t)\rangle = \frac{\left(I + \frac{-i\delta t H}{\hbar}\right)|\psi(t)\rangle}{\sqrt{\langle\psi(t)|\left(I + \frac{i\delta t H^\dagger}{\hbar}\right)\left(I + \frac{-i\delta t H}{\hbar}\right)|\psi(t)\rangle}}$$

4. Complete a trajectory

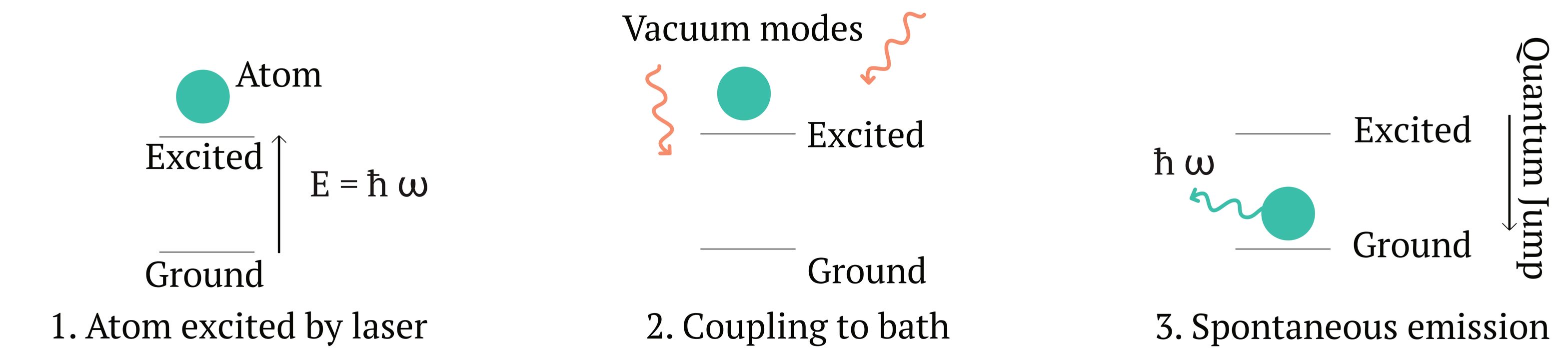
5. Average over many trajectories

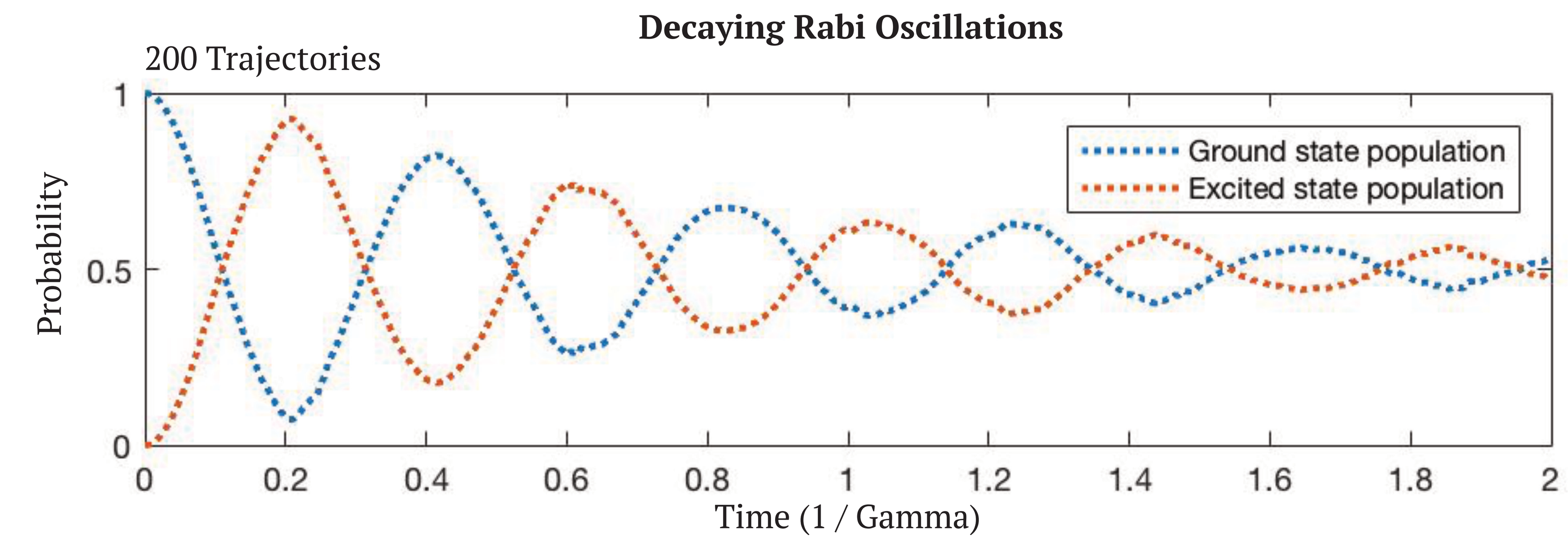
RESULTS

Quantum Jumps in Energy



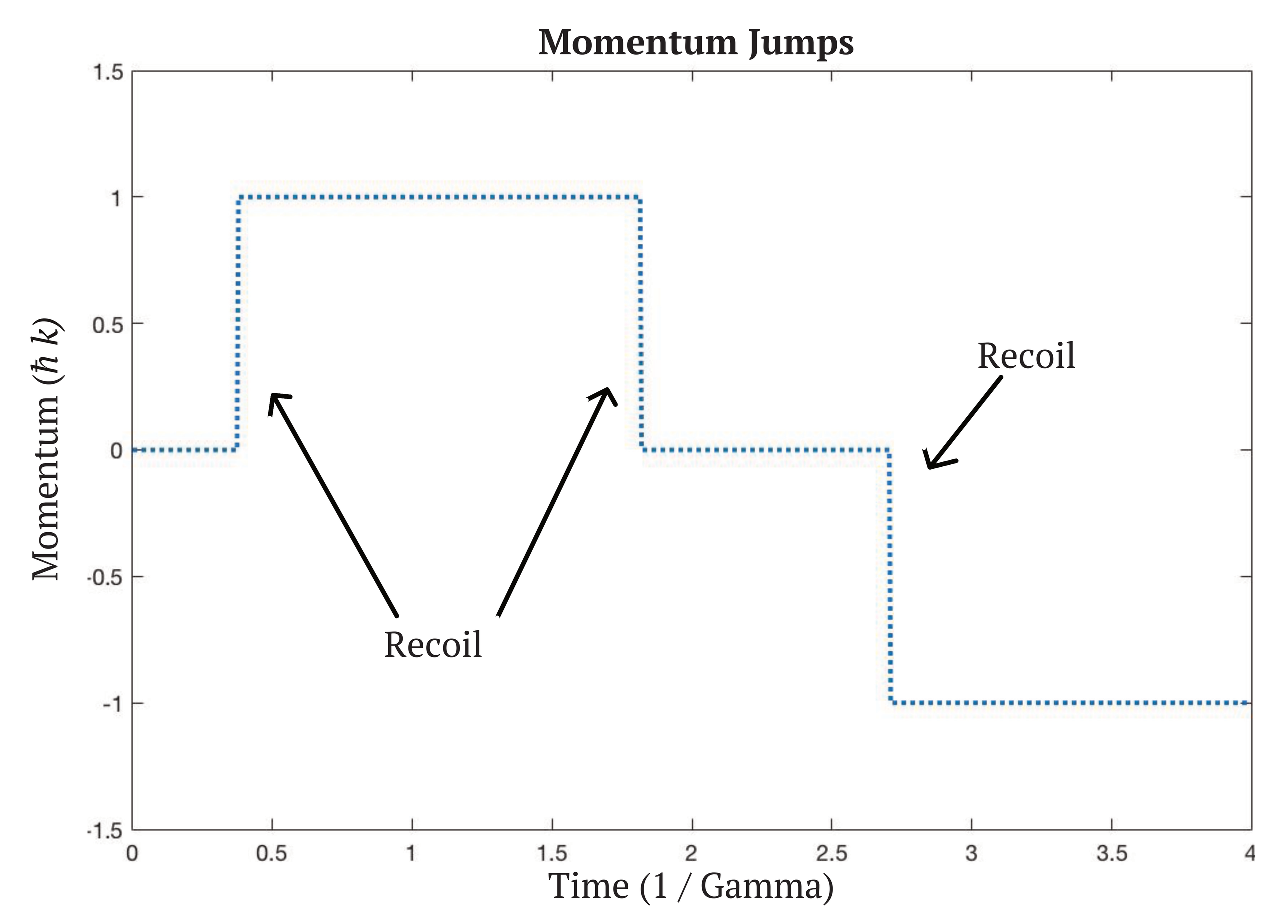
A single Monte Carlo Wave Function trajectory shows Rabi oscillations. Each quantum jump event brings the atom back to the ground state.



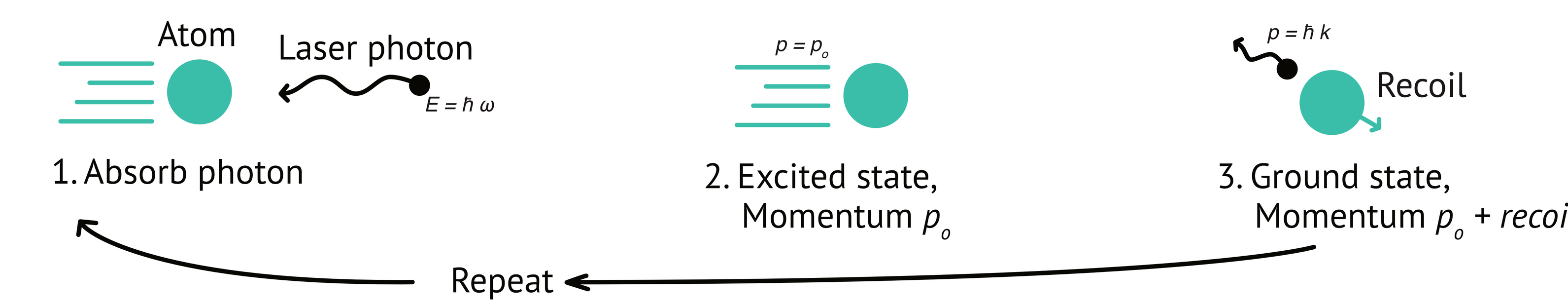


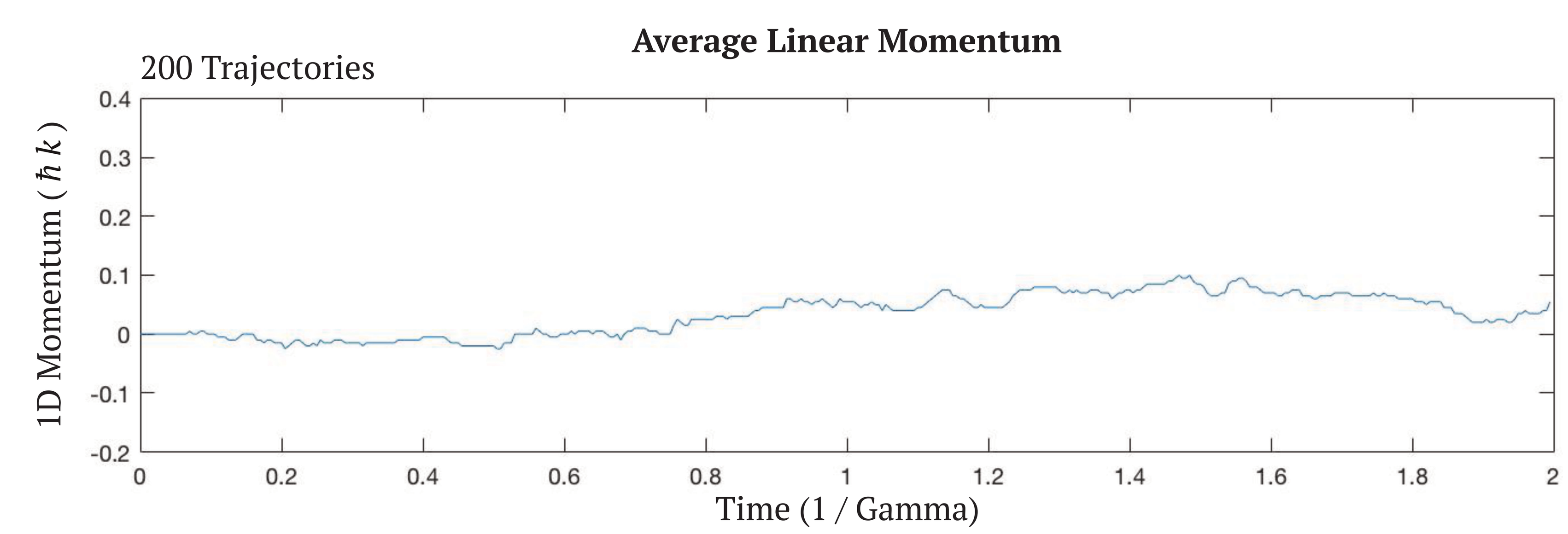
The average of many trajectories yields "Decaying Rabi Oscillations" because each jump causes decoherence. Over time, each energy level becomes equally likely.

Quantum Jumps with One Dimensional Recoil



During each of three quantum jump events, the atom recoils and changes its momentum by one unit $\hbar k$.

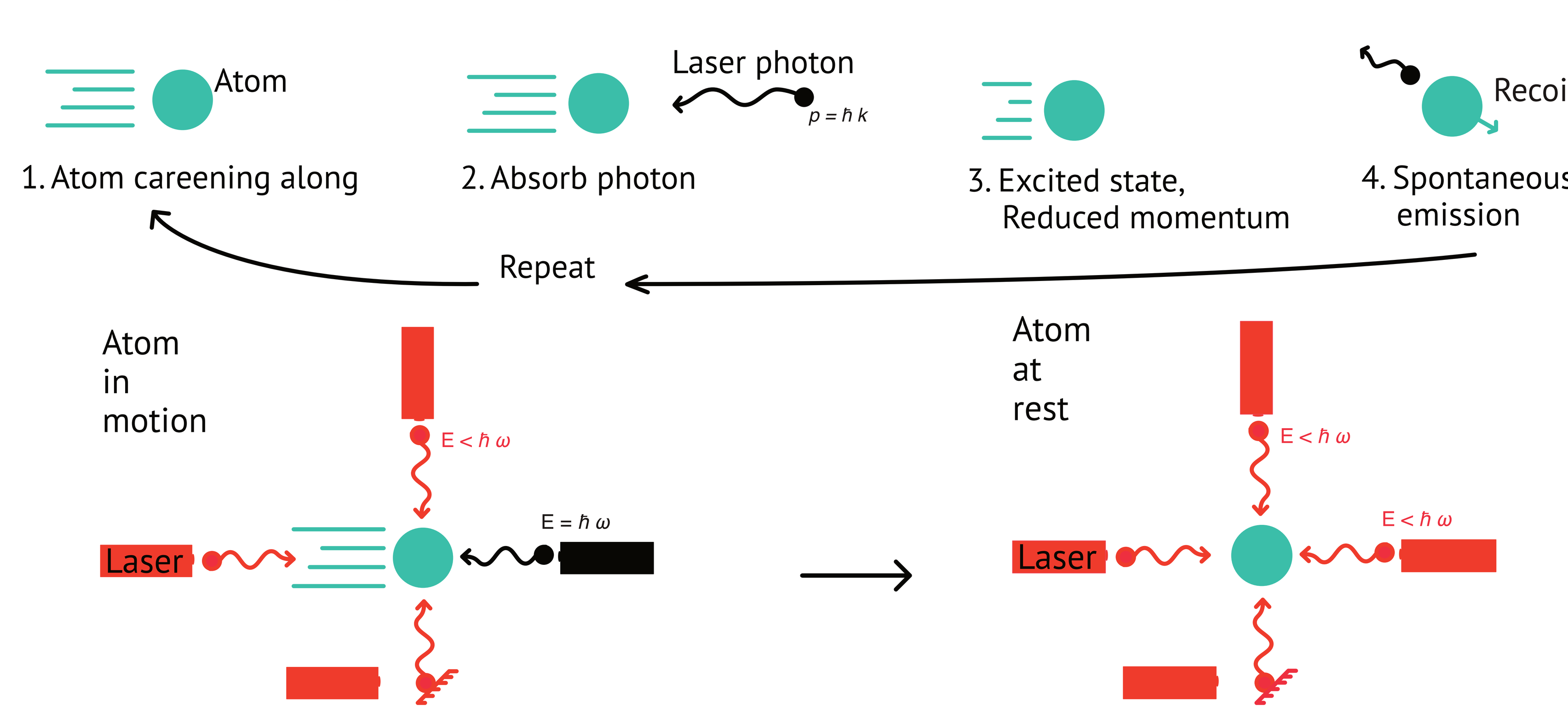




Spontaneous emission occurs in a random direction. Therefore, the average of many trajectories shows the atom remaining near zero $\hbar k$ momentum.

EXTENSIONS

Laser Cooling



Future Work

Our goal is to extend the Monte Carlo Wave Function simulations to treat a fully quantum mechanical model of laser cooling. This extension requires: three dimensional recoil, laser detuning, interactions with multiple interfering laser beams, and considerations for a cloud of atoms in a mixed state.

References

Christopher Corder, Brian Arnold, Xiang Hua, and Harold Metcalf, "Laser cooling without spontaneous emission," Phys. Rev. Lett. 114, 043002 (2015).

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