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Rate equations for the control of Yb-171 ions

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Trapped ions are promising candidates to use as qubits in quantum computers, offering long coherence times, scalability, and precise control of the states of each ion individually by means of lasers. The long-term goal of this quantum control project is to achieve unsharp measurements with two isotopes of ytterbium, Yb-171 and Yb-174, in a linear Paul trap. To predict and interpret experimental results for one of the species, Yb-171, we numerically model the atom-radiation interactions using rate equations. Rate equations are a set of coupled, first-order differential equations describing the time-dependent evolution of the ion's hyperfine state populations due to transitions between levels.

We semi-classically model the interaction between the ion valence structure and lasers, which includes electric dipole and electric quadrupole transitions. Using the model, we analyse hyperfine state population dynamics to gain insights on how to increase the efficiency of and estimate timescales for various quantum control processes used experimentally. These processes include doppler cooling, state preparation , electron shelving and state detection. Ions are doppler cooled to reduce their kinetic energy so that they remain trapped, enabling precise control and manipulation. Doppler cooling is estimated in the simulation as an accumulation of spontaneous emission due to driving a transition. State preparation initialises the ion into the qubit ground state. We model electron shelving by populating and depopulating a long-lived metastable state by pumping an electric quadrupole transition. State detection is performed by pumping a closed loop transition that produces measurable fluorescence. To recover efficiency of these processes, several additional lasers are used to depopulate dark states.

Understanding how these processes influence the ion's state is crucial for optimizing them, ultimately improving future experimental control and efficiency in the laboratory.

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