August 14th 2024

UW Trapped Ion Lab

Quantum State Detection of a Barium-138 Ion in a Non-steady State Evolution

Ahrin (Irene) Yang
Advisor: Dr. Boris Blinov

Constructing a physical Qubit

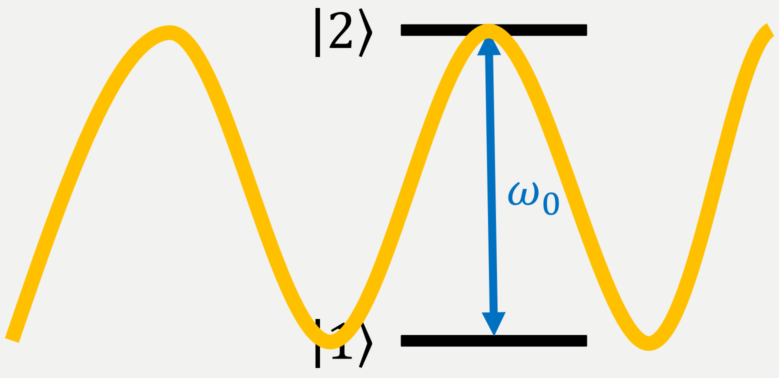
Qubit: Most basic unit of information for Quantum Computing

Important Criteria for a physical qubit

1. Scalability
2. Long and Stable states
3. Measurement Capability

Barium Ion Qubit → State Dependent Fluorescence

2-level atom interacting with External Field



Bare Hamiltonian

$$\hat{H}_0 = E_1|1\rangle\langle 1| + E_2|2\rangle\langle 2| = \begin{bmatrix} E_1 & 0 \\ 0 & E_2 \end{bmatrix} = \hbar \begin{bmatrix} \omega_1 & 0 \\ 0 & \omega_2 \end{bmatrix}$$

$$= \hbar \begin{bmatrix} 0 & 0 \\ 0 & \omega_0 \end{bmatrix} \quad (\omega_0 = \omega_2 - \omega_1)$$

Interaction Hamiltonian

$$\hat{H}_1(t) = e\vec{r} \cdot \overrightarrow{E_0} \cos(\omega t) = \frac{\hbar}{2}\Omega\left(e^{i\omega t}|1\rangle\langle 2| + e^{-i\omega t}|2\rangle\langle 1|\right)$$

Rabi frequency: $\Omega = \frac{eE_0}{\hbar}\langle 1|\vec{r} \cdot \vec{e}_{rad}|2\rangle$

Total Hamiltonian

Bare Hamiltonian

$$\hat{H}_0 = \hbar \begin{bmatrix} 0 & 0 \\ 0 & \omega_0 \end{bmatrix} \quad (\omega_0 = \omega_2 - \omega_1)$$

Interaction Hamiltonian

$$\hat{H}_1(t) = \frac{\hbar}{2}\Omega\left(e^{i\omega t}|1\rangle\langle 2| + e^{-i\omega t}|2\rangle\langle 1|\right)$$

$$\hat{H} = \hat{H}_0 + \hat{H}_1 = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega e^{i\omega t} \\ \Omega e^{-i\omega t} & 2\omega_0 \end{bmatrix}$$

Rotating Frame Transformation

$$\tilde{H} = \hat{U}\hat{H}\hat{U}^\dagger$$

$$\hat{U} = e^{i\omega t|2\rangle\langle 2|}$$

$$\tilde{H} = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega \\ \Omega & 2\Delta \end{bmatrix} \quad (\Delta = \omega - \omega_0)$$

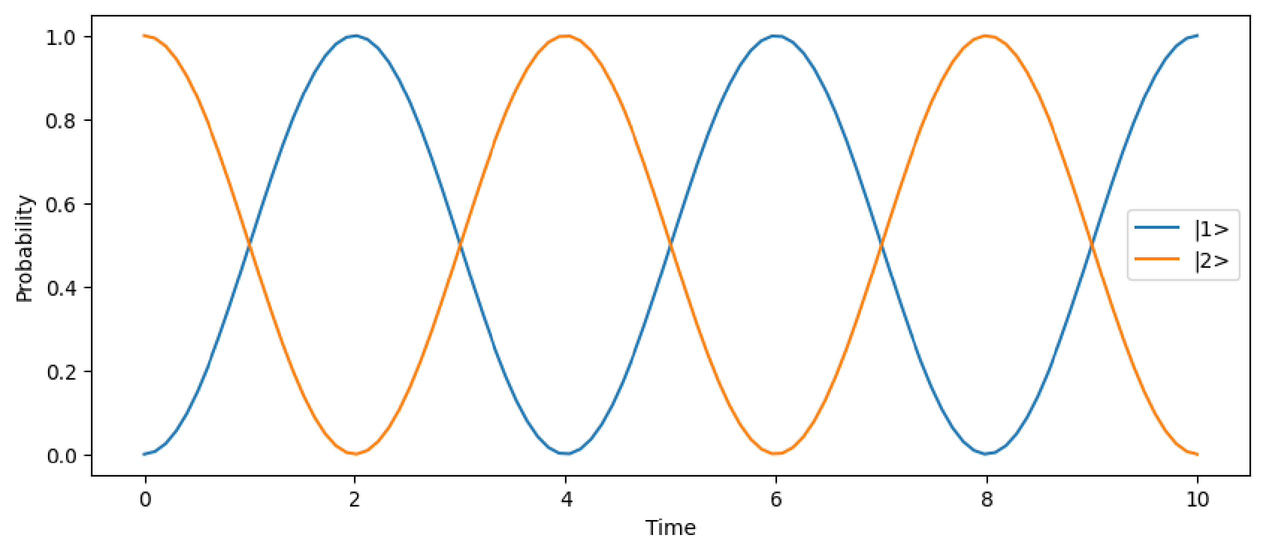
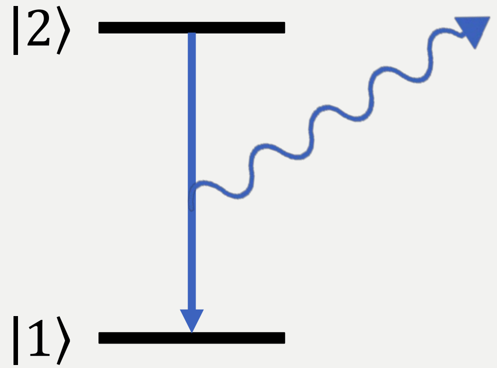


Figure 1. Time evolution of 2-level atom interacting with an external resonant electric field

Spontaneous Decay



Lifetime τ

Decay Rate $\Gamma = \tau^{-1}$

Collapse Operator $C = \sqrt{\Gamma}|1\rangle\langle 2|$

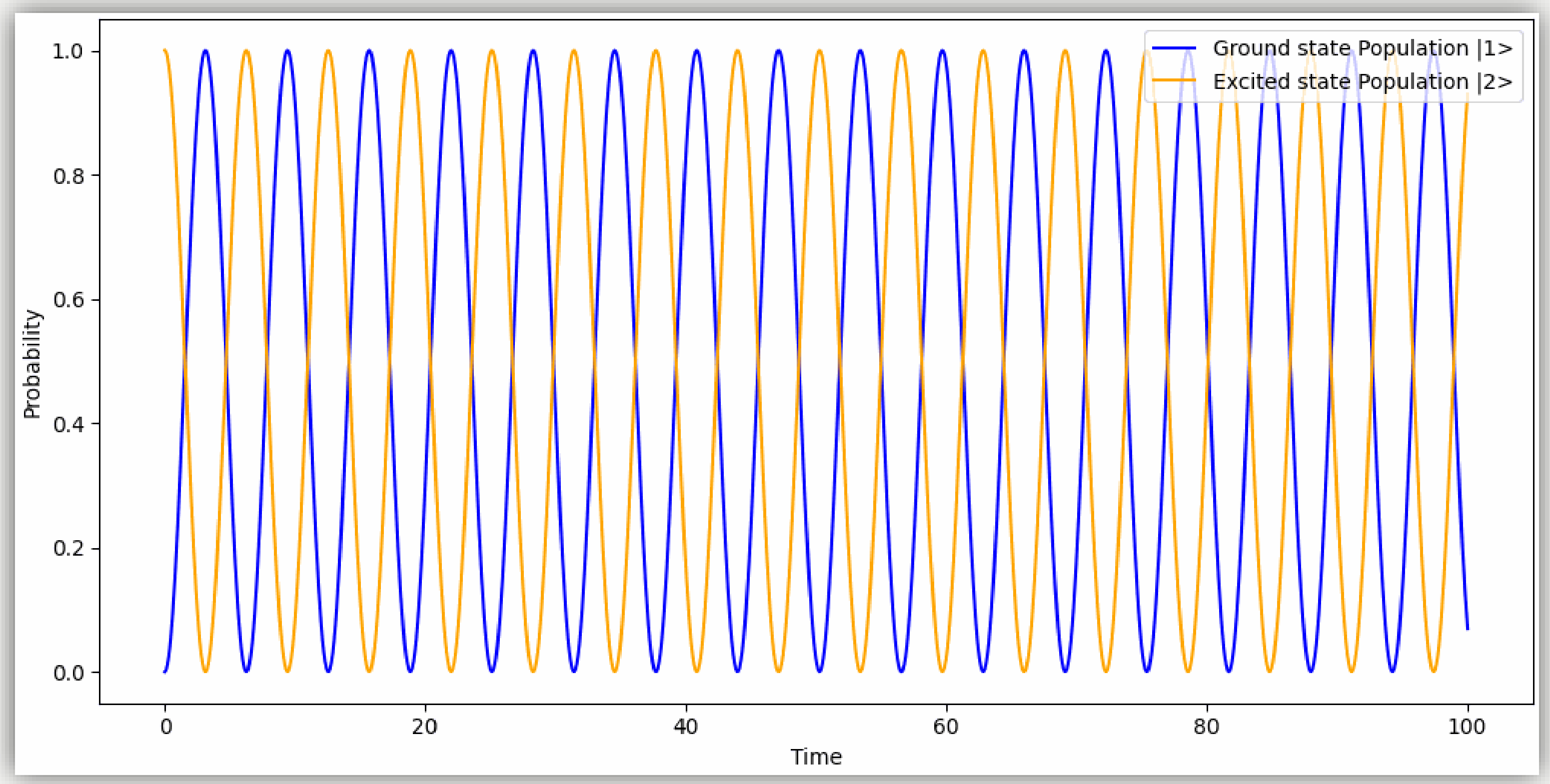
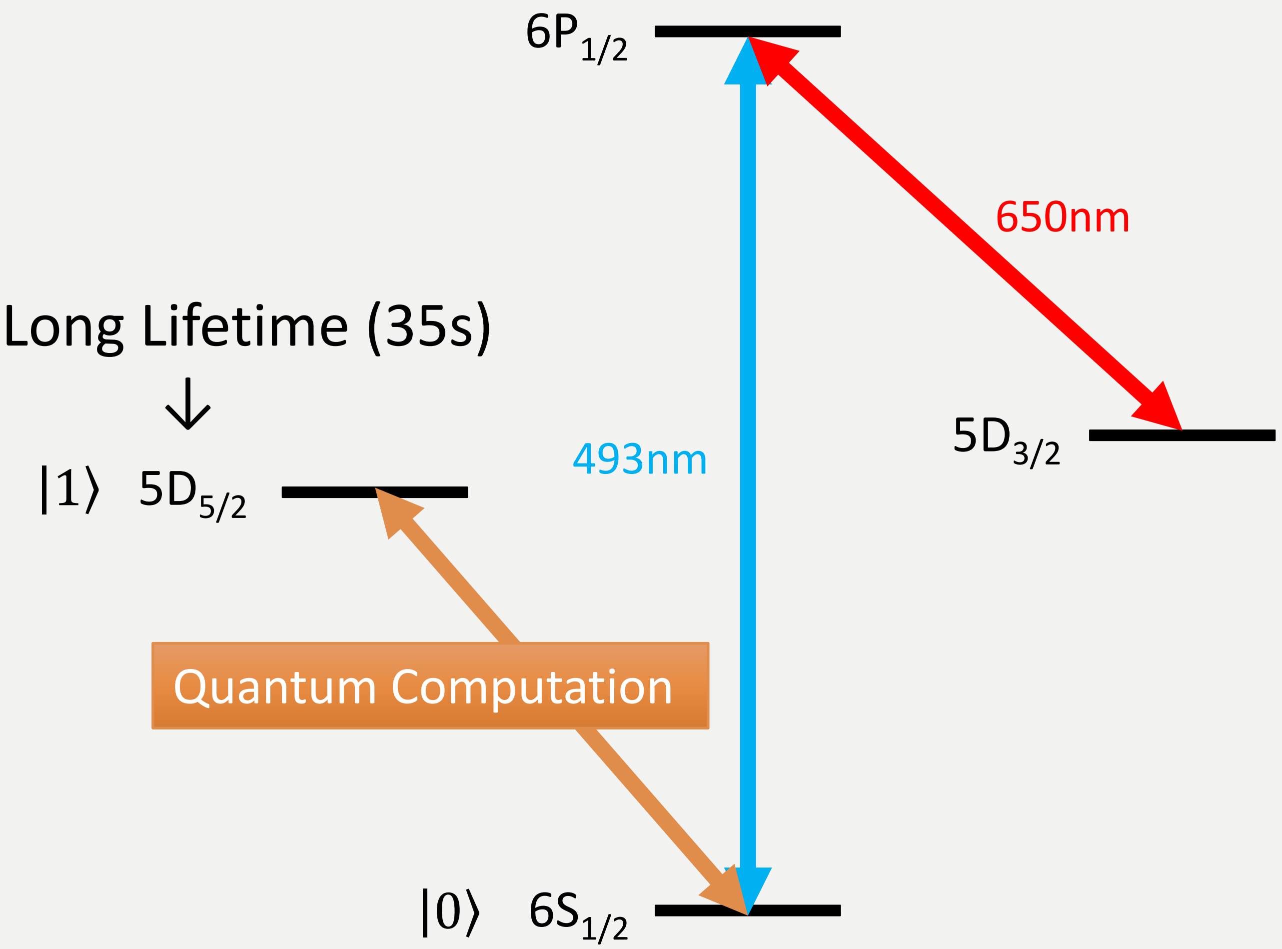


Figure 2. Change in time evolution of 2-level atom interacting with an external resonant electric field with increasing decay rate

State Detection of $^{138}Ba^{+}$ qubit



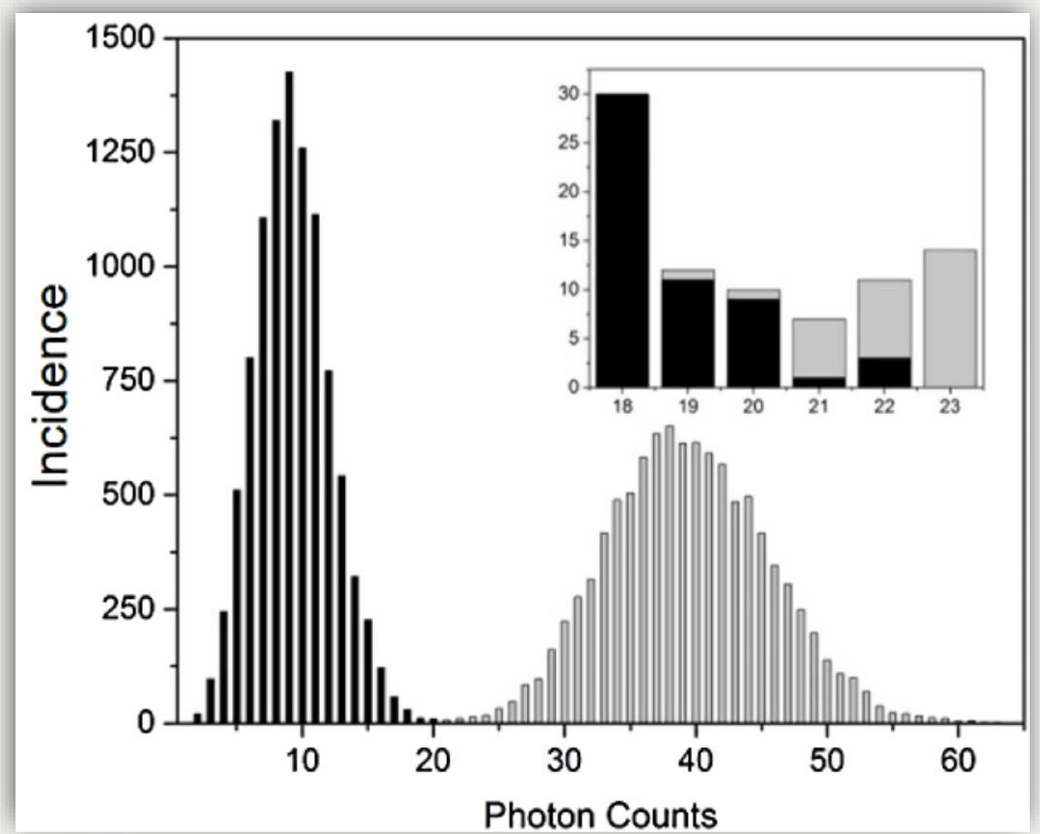
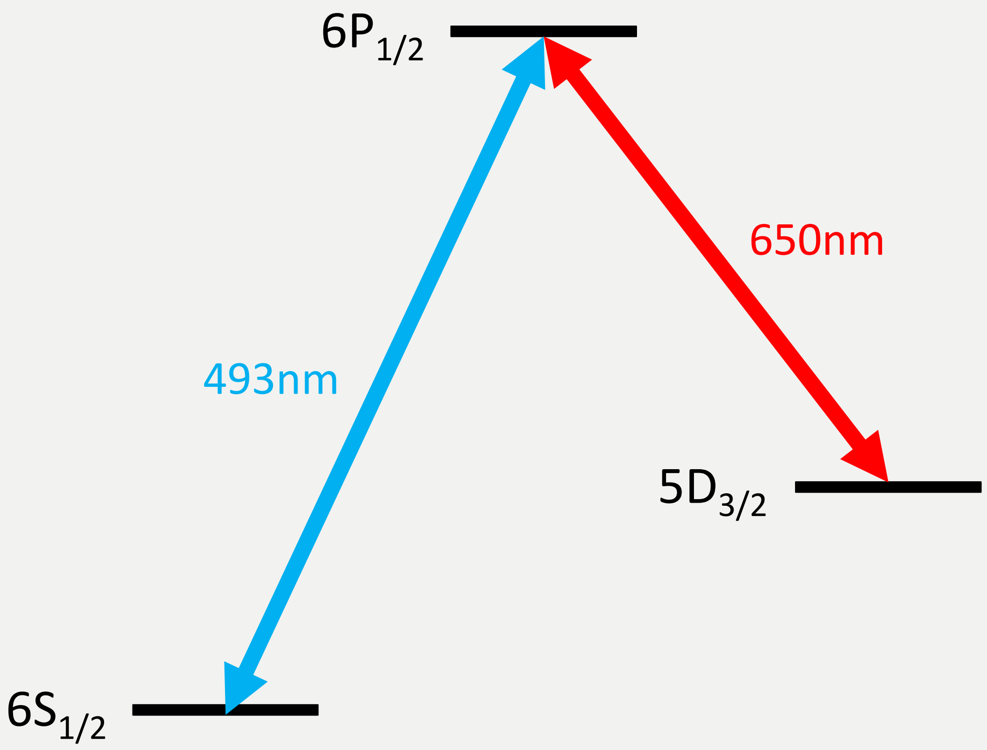


Figure 3. Photon count histogram of barium ion qubit for different states (Black: ground state, Gray: excited state). Inset shows overlap region of two histograms (adapted from Yum et al., 2017).

Coherent Dark States



Electron gets trapped in "dark states"

$$c_S\Omega_S = -c_D\Omega_D$$

$$(\ |\psi\rangle = c_S|S\rangle + c_D|D\rangle + 0|P\rangle\ )$$

Destructive Interference

Modeling 3 level system of $^{138}Ba^{+}$

$S_{1/2} = |0\rangle$

$P_{1/2} = |1\rangle$

$D_{3/2} = |2\rangle$

$$\hat{H} = \begin{bmatrix} 0 & \Omega_{493} & 0 \\ \Omega_{493} & 0 & \Omega_{650} \\ 0 & \Omega_{650} & 0 \end{bmatrix}$$

*no detuning

Collapse Operators

$\hat{C}_S = \Gamma_S |0\rangle\langle 1|$

$\hat{C}_D = \Gamma_D |2\rangle\langle 1|$

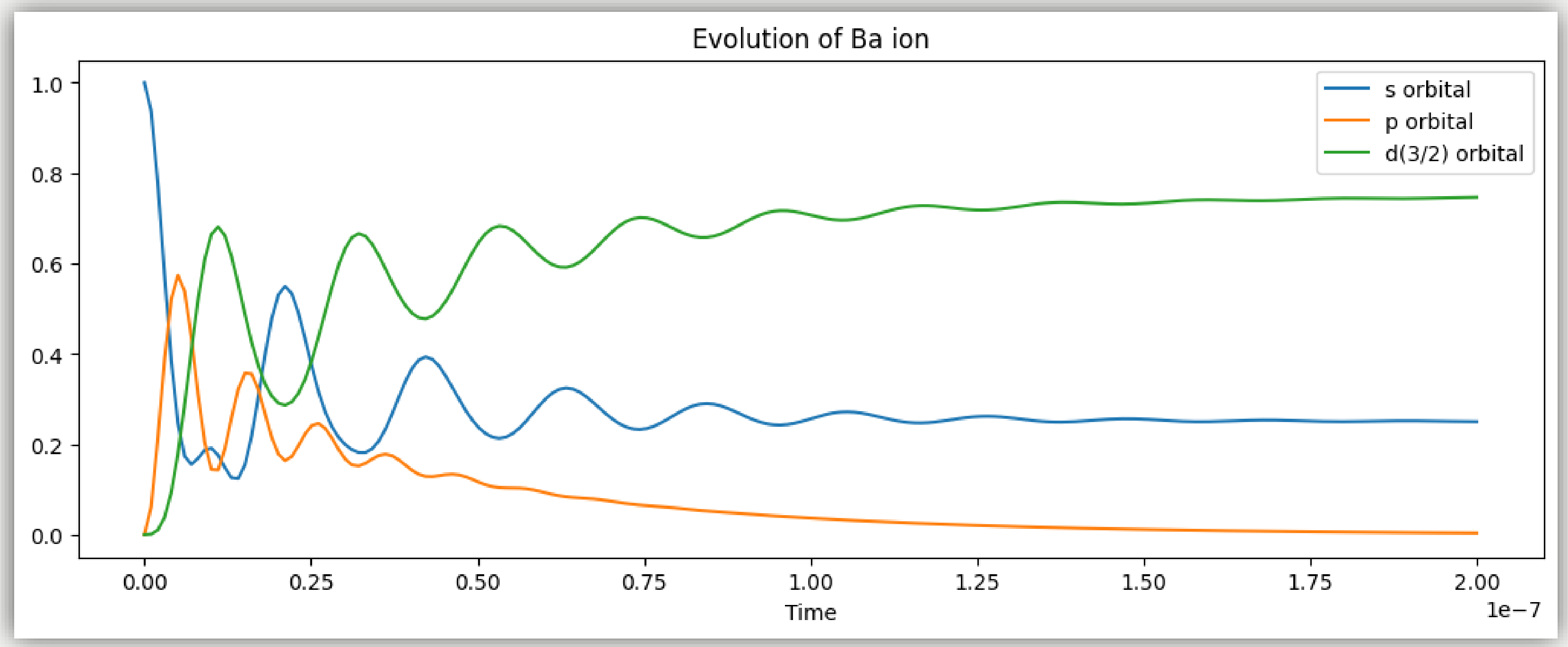


Figure 4. Time evolution of a 3-level Ba ion reaching a steady dark state while both resonance lasers applied

Alternating laser pulses

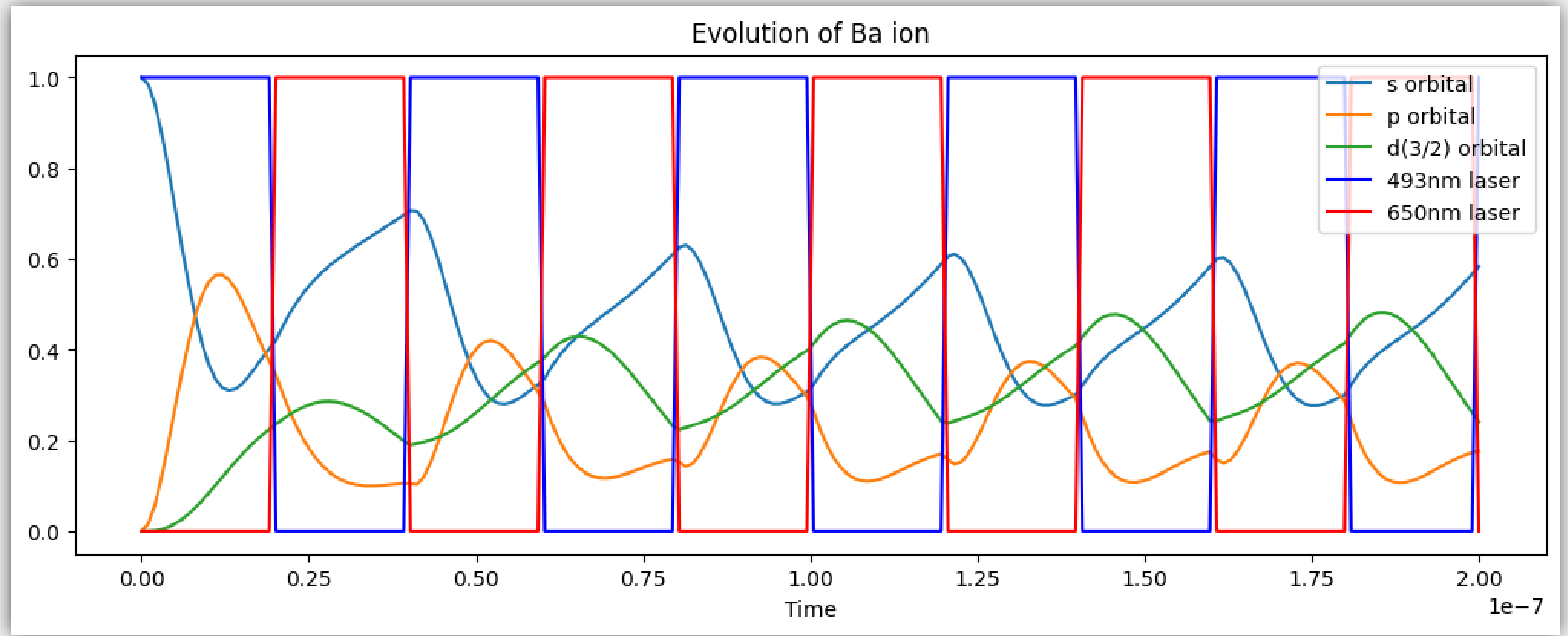


Figure 5. Time evolution of 3-level Ba ion while two resonance lasers are alternating pulses

Optimizing Laser pulse intervals

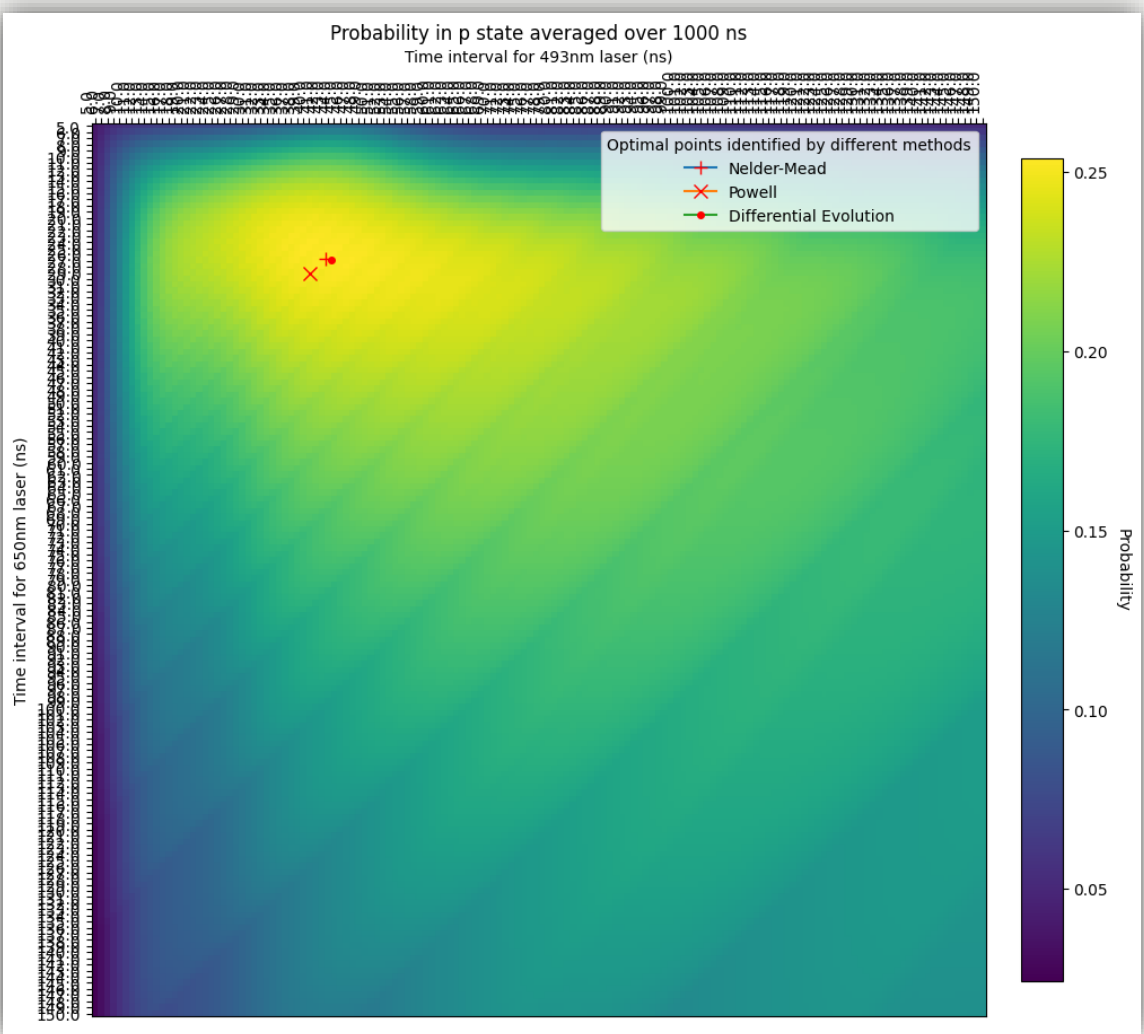


Figure 6. 3-level Ba ion's average p state probability while varying interval of laser pulses

Optimal Interval

493nm laser: 42.74 ns

650nm laser: 26.64 ns

Average probability in P state: 0.254

Optimizing Laser pulse intervals

Optimal Interval

493nm laser: 42.74 ns

650nm laser: 26.64 ns

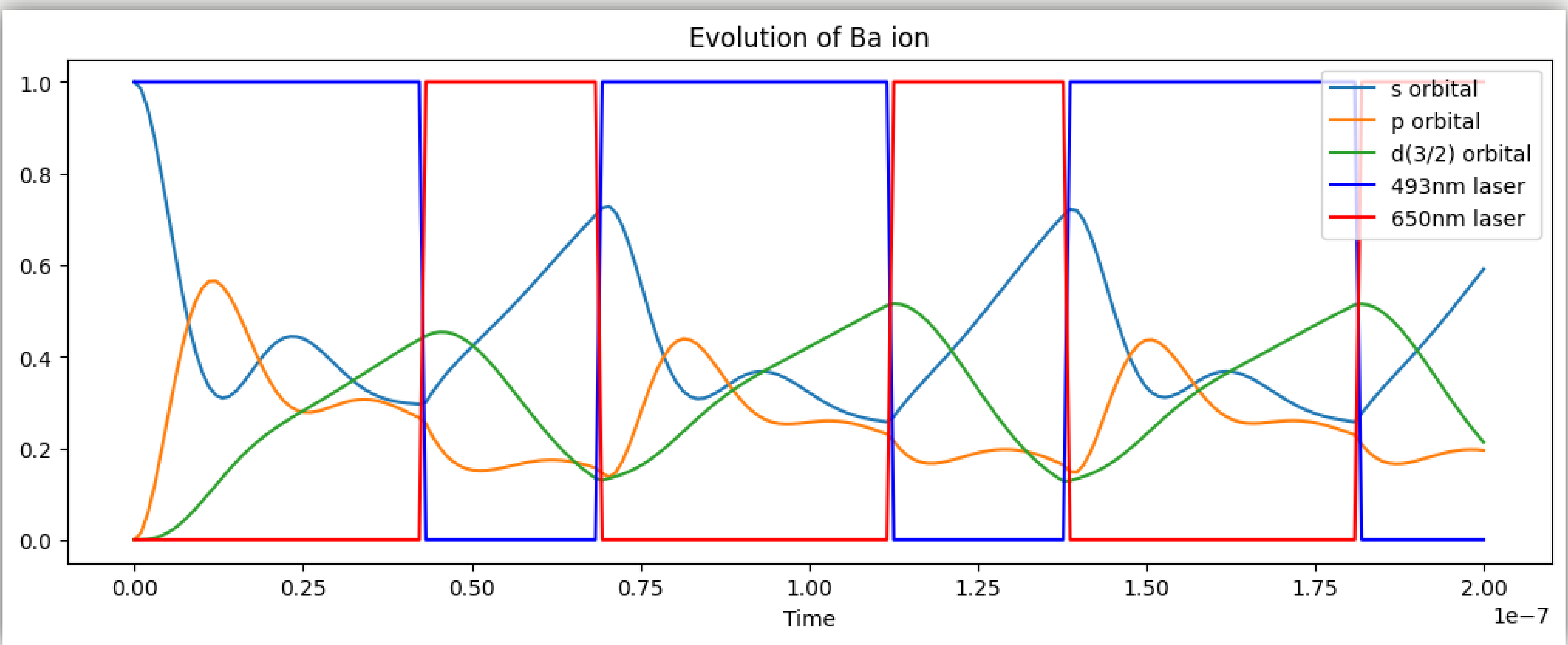
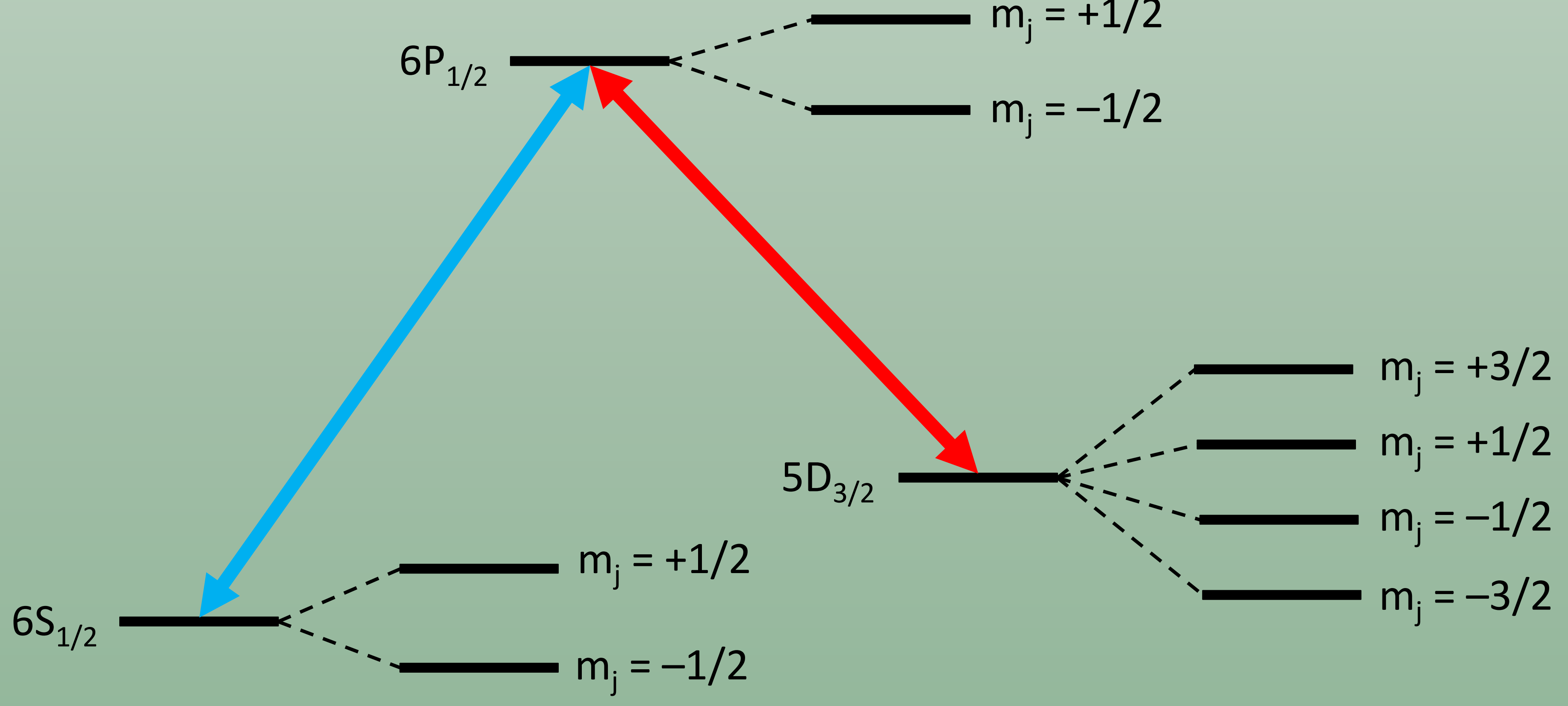


Figure 7. Time evolution of 3-level Ba ion while alternating two resonance pulses at optimal interval lengths identified by optimization algorithms

Zeeman Splitting

Magnetic Field



Selection Rule

Quantization Axis: direction along which magnetic field is aligned (z-axis)

Photon
$j = 1$
$m_j = -1,0,1$

Transition Rules
1. $\Delta l = \pm 1$
2. $\Delta m_j = -1,0,1$

$\Delta m_j = +1$: σ_+ Transition
$\Delta m_j = -1$: σ_- Transition
$\Delta m_j = 0$: π Transition

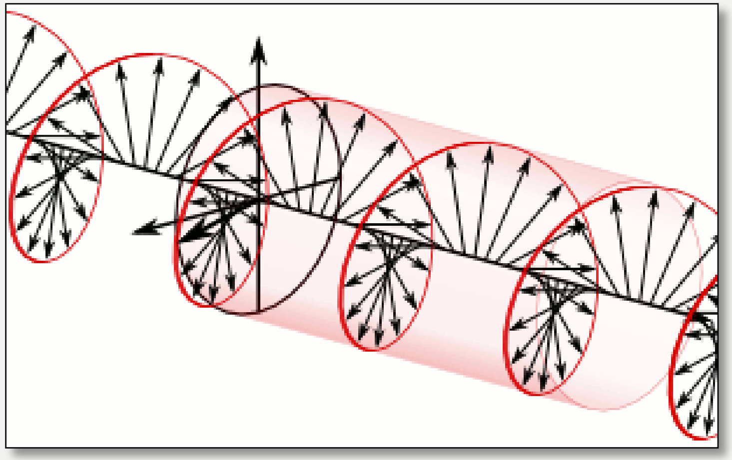


Figure 8. Right-handed circularly polarized light (Image by Dave3457, Public Domain via Wikimedia Commons)

Electric field
σ_+ Right circular polarization
σ_- Left circular polarization
π Linear Polarization along the quantization axis

Modeling 8 level system of $^{138}Ba^+$

$S_{-1/2} = |0\rangle$

$S_{+1/2} = |1\rangle$

$P_{-1/2} = |2\rangle$

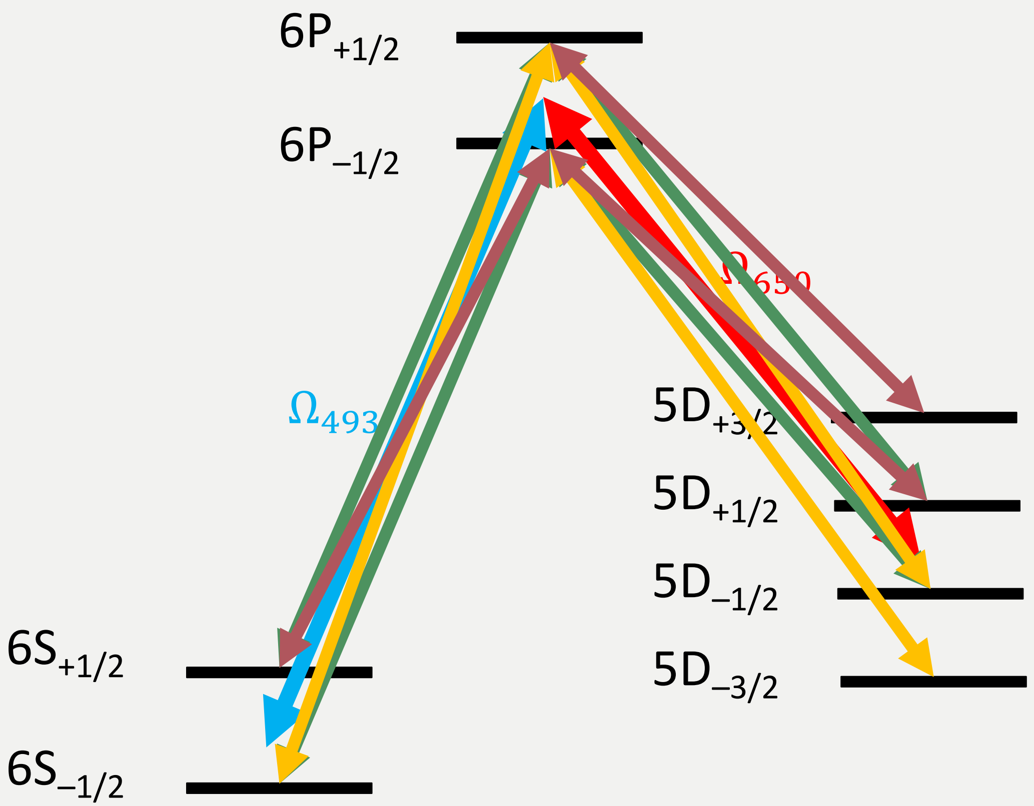
$P_{+1/2} = |3\rangle$

$D_{-3/2} = |4\rangle$

$D_{-1/2} = |5\rangle$

$D_{+1/2} = |6\rangle$

$D_{+3/2} = |7\rangle$



$\vec{B}$ field is along z-axis

$$\hat{e}_{rad} = \begin{bmatrix} \sin\theta \\ 0 \\ \cos\theta \end{bmatrix}$$

z-component: drives π transition
x-component: drives a linear combination of sigma+ and sigma– transitions

Optimizing Different Polarization Angle

$$\hat{e}_{493} = \begin{bmatrix} \sin\alpha \\ 0 \\ \cos\alpha \end{bmatrix} \qquad \hat{e}_{650} = \begin{bmatrix} \sin\beta \\ 0 \\ \cos\beta \end{bmatrix}$$

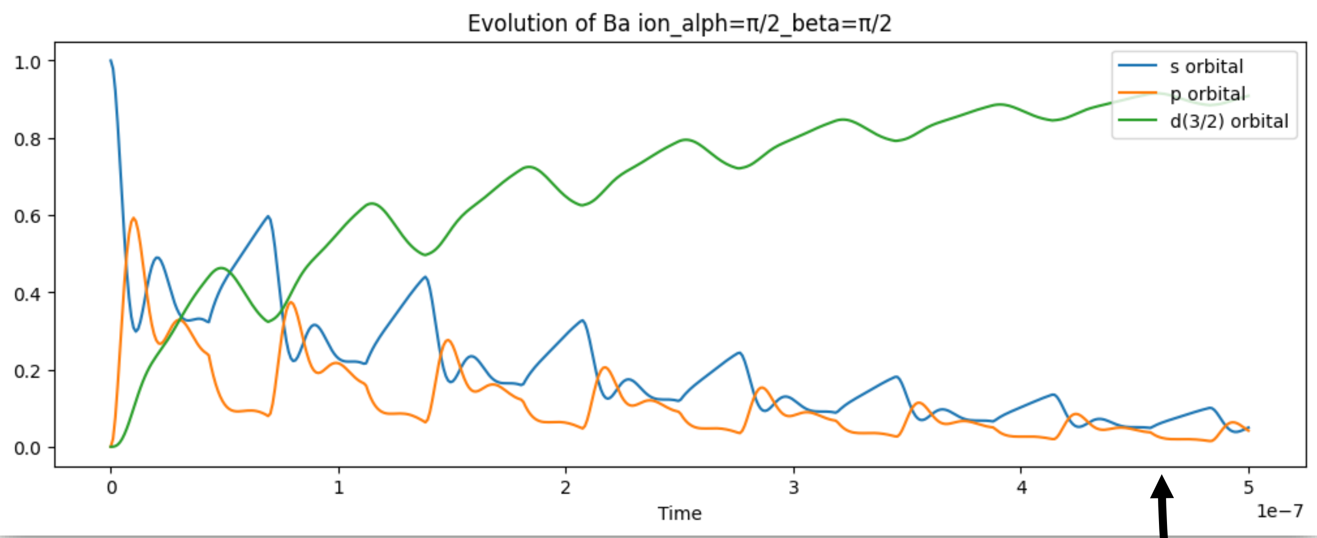


Figure 9. Time evolution of 8-level Ba system over 500 ns with polarization angle α=90˚, β=90˚

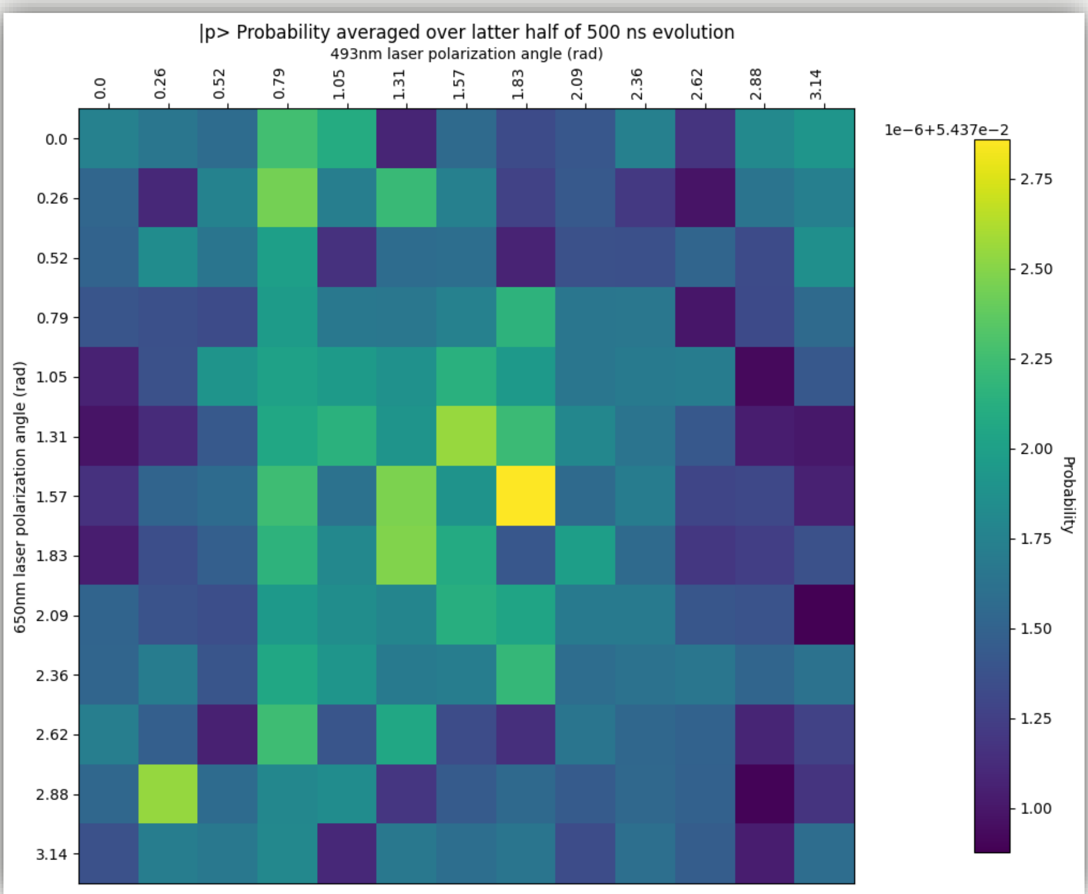


Figure 10. Heatmap of 8-level Ba ion's average p state probability while varying polarization angles

Approcaching zero

Optimizing Laser Intervals

Optimal Interval

493nm laser: 39.6 ns 650nm laser: 81.7 ns

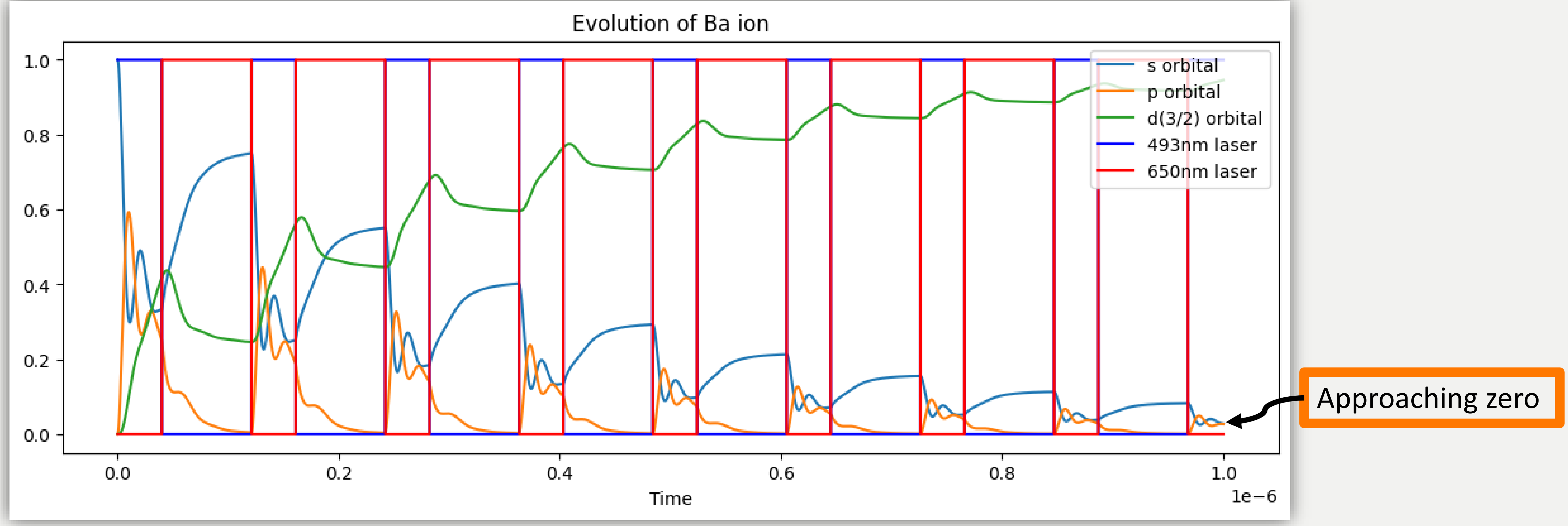
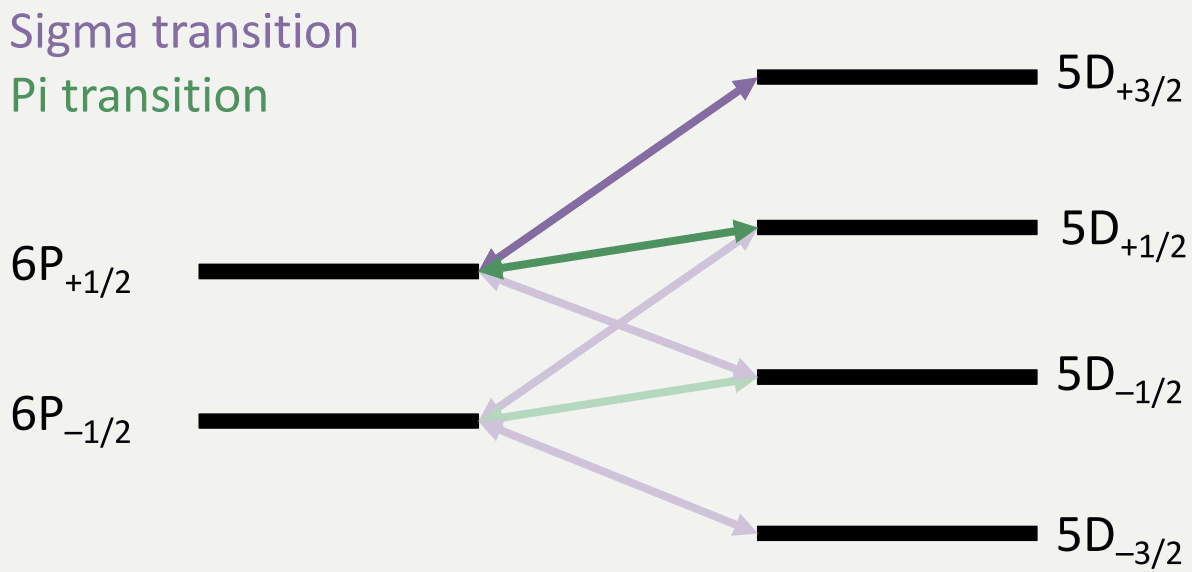


Figure 11. Time evolution of 8-level Ba ion while alternating two resonance pulses at optimal interval lengths identified by optimization algorithms

Coherent Dark state w/n $D_{3/2}$ orbital



→ Alternate polarization

Alternating Polarization of 650nm Laser

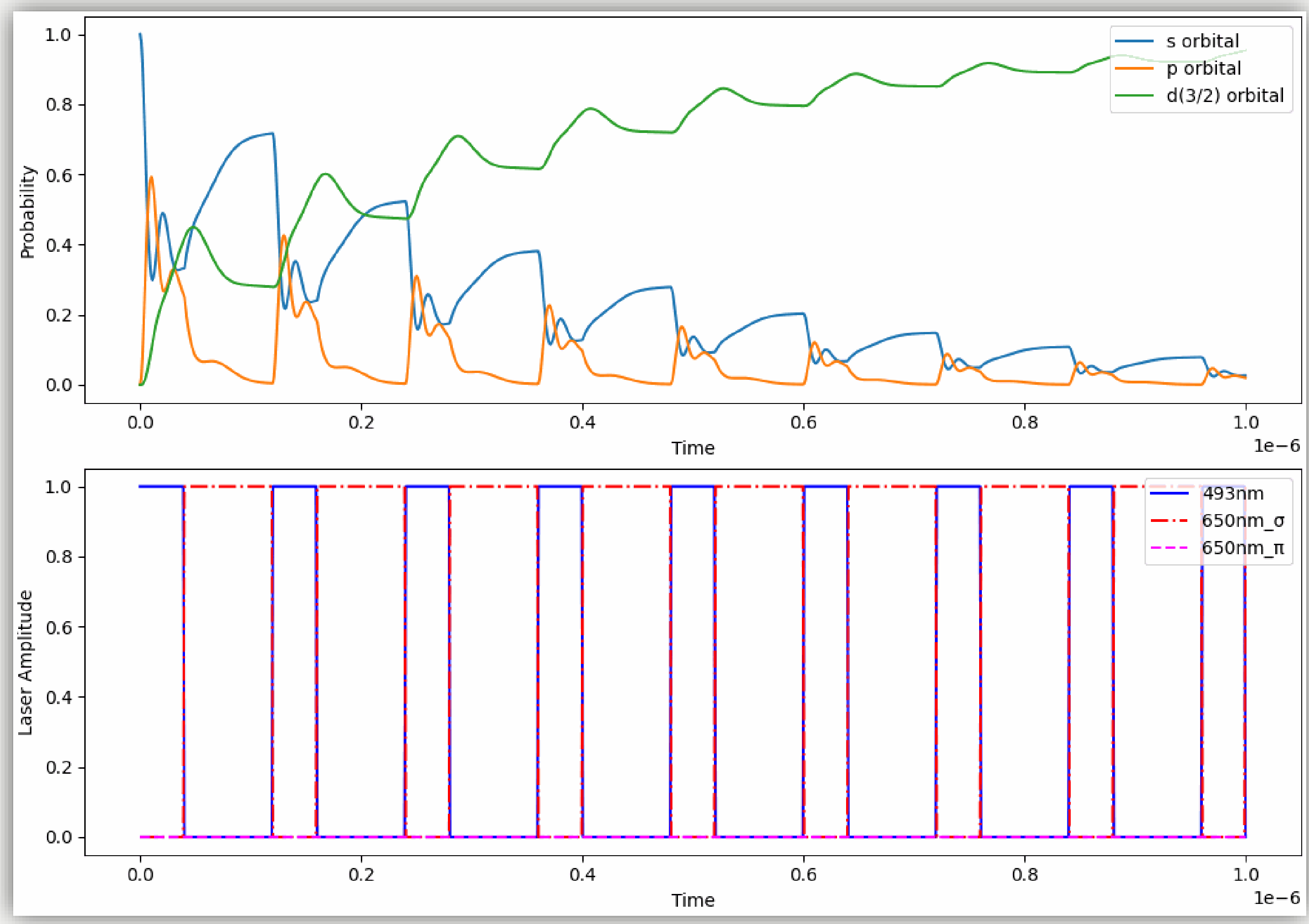


Figure 12. 8-level Ba ion time evolution for varying interval lengths of z-polarized laser pulses

Optimizing interval of polarized Laser pulses

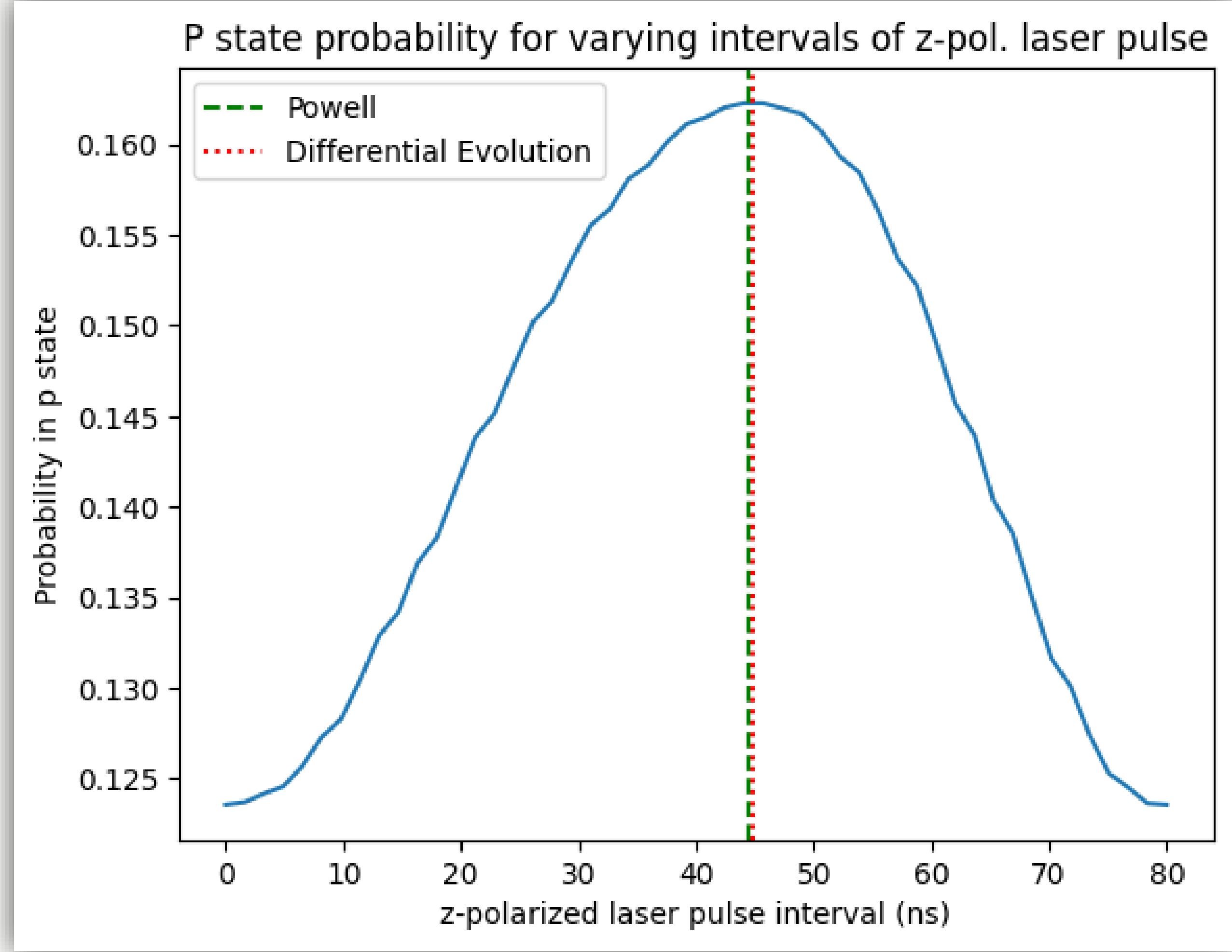


Figure 13. Probability in p state for varying interval lengths of z-polarized laser pulses

within 80 ns of 650 nm laser pulse

Optimal intervals

z-polarized laser pulse: 44.10 ns

x-polarized laser pulse: 35.90 ns

Average p state probability: 0.162

Optimal interval of polarized laser pulses

Optimal Interval

z-pol. 650nm laser: 35.90 ns

x-pol. 650 nm laser : 44.10 ns

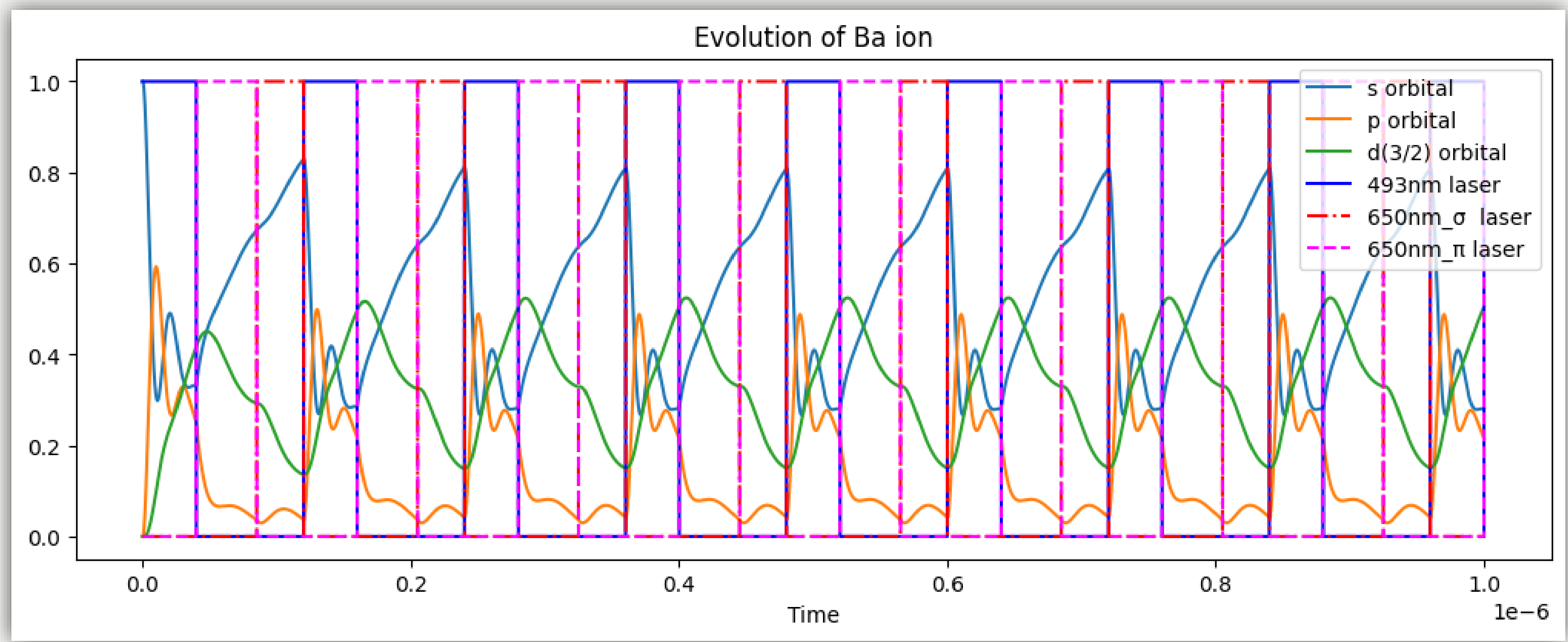


Figure 14. Time evolution of 8-level Ba ion while alternating differently polarized 650 nm laser pulses at optimal intervals

Future Work

- Study more theory to understand and reason the results
  - Coherent dark states
  - Solve Hamiltonian and Eigenstates
- Changing polarization
  - Distinguishing sigma+ and sigma– transitions
  - Elliptical polarization
- Coherent Bright States

Thank You, Questions?

Special Thanks to,

- The Trapped Ion lab team

  Dr. Boris Blinov, Aaron Hoyt, Carl Thomas
- Institute of Nuclear Theory
- National Science Foundation
- UW Physics REU '24 cohort

Back up: 8 level $^{138}Ba^{+}$ Hamiltonian

$$H = \begin{pmatrix}
\Delta_g - u & 0 & \frac{\Omega_g}{\sqrt{3}}\cos\alpha & -\frac{\Omega_g}{\sqrt{3}}\sin\alpha & 0 & 0 & 0 & 0 \\
0 & \Delta_g + u & -\frac{\Omega_g}{\sqrt{3}}\sin\alpha & -\frac{\Omega_g}{\sqrt{3}}\cos\alpha & 0 & 0 & 0 & 0 \\
\frac{\Omega_g}{\sqrt{3}}\cos\alpha & -\frac{\Omega_g}{\sqrt{3}}\sin\alpha & -\frac{1}{3}u & 0 & -\frac{\Omega_r}{2}\sin\alpha & -\frac{\Omega_r}{\sqrt{3}}\cos\alpha & \frac{\Omega_r}{2\sqrt{3}}\sin\alpha & 0 \\
-\frac{\Omega_g}{\sqrt{3}}\sin\alpha & -\frac{\Omega_g}{\sqrt{3}}\cos\alpha & 0 & \frac{1}{3}u & 0 & -\frac{\Omega_r}{2\sqrt{3}}\sin\alpha & -\frac{\Omega_r}{\sqrt{3}}\cos\alpha & \frac{\Omega_r}{2}\sin\alpha \\
0 & 0 & -\frac{\Omega_r}{2}\sin\alpha & 0 & \Delta_r - \frac{6}{5}u & 0 & 0 & 0 \\
0 & 0 & -\frac{\Omega_r}{\sqrt{3}}\cos\alpha & -\frac{\Omega_r}{2\sqrt{3}}\sin\alpha & 0 & \Delta_r - \frac{2}{5}u & 0 & 0 \\
0 & 0 & \frac{\Omega_r}{2\sqrt{3}}\sin\alpha & -\frac{\Omega_r}{\sqrt{3}}\cos\alpha & 0 & 0 & \Delta_r + \frac{2}{5}u & 0 \\
0 & 0 & 0 & \frac{\Omega_r}{2}\sin\alpha & 0 & 0 & 0 & \Delta_r + \frac{6}{5}u
\end{pmatrix}$$

Figure 15. Hamiltonian of 8-level Barium Ion system (adapted from Sosnova, 2020)

Energy shift

$$\Delta E = m_J g_J u$$
$$u = \mu_B \vec{B}$$

Δ detuning

Constants
result of angular integral (inner product) evaluating the coupling between the states

$$\langle i | e\vec{r} \cdot \vec{e}_{rad} | j \rangle$$