Towards high fidelity, fast gates in ^{137}Ba$^+$

C. Liu [1], J. Phua [1], S. Chakraborty [1], M. Mukherjee [1]

[1]Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543

Introduction

Single and two-qubit gates in the electronic ground state hyperfine manifold in atoms and ions benefit from reduced gate times when mediated by Raman laser beams rather than direct microwave radiation. While high-powered lasers with tight focusing can generate stronger electric fields than microwave radiation emitted from a horn antenna, high-intensity Raman beams also reduce fidelity through uncompensated differential light shifts and off-resonant photon scattering. Increasing the Raman laser detuning suppresses scattering but lengthens the gate time, requiring higher optical power to compensate. In barium ions, Raman transitions are typically driven with $532\,$nm lasers, though this wavelength is not necessarily optimal for minimising differential light shifts. We present our ongoing theoretical efforts to identify the optimal wavelength that minimises differential light shifts in Raman transitions applied to the ground-state clock qubits of ^{137}Ba$^+$, while balancing the competing demands of short gate times and high fidelity.

Conceptual Preliminaries

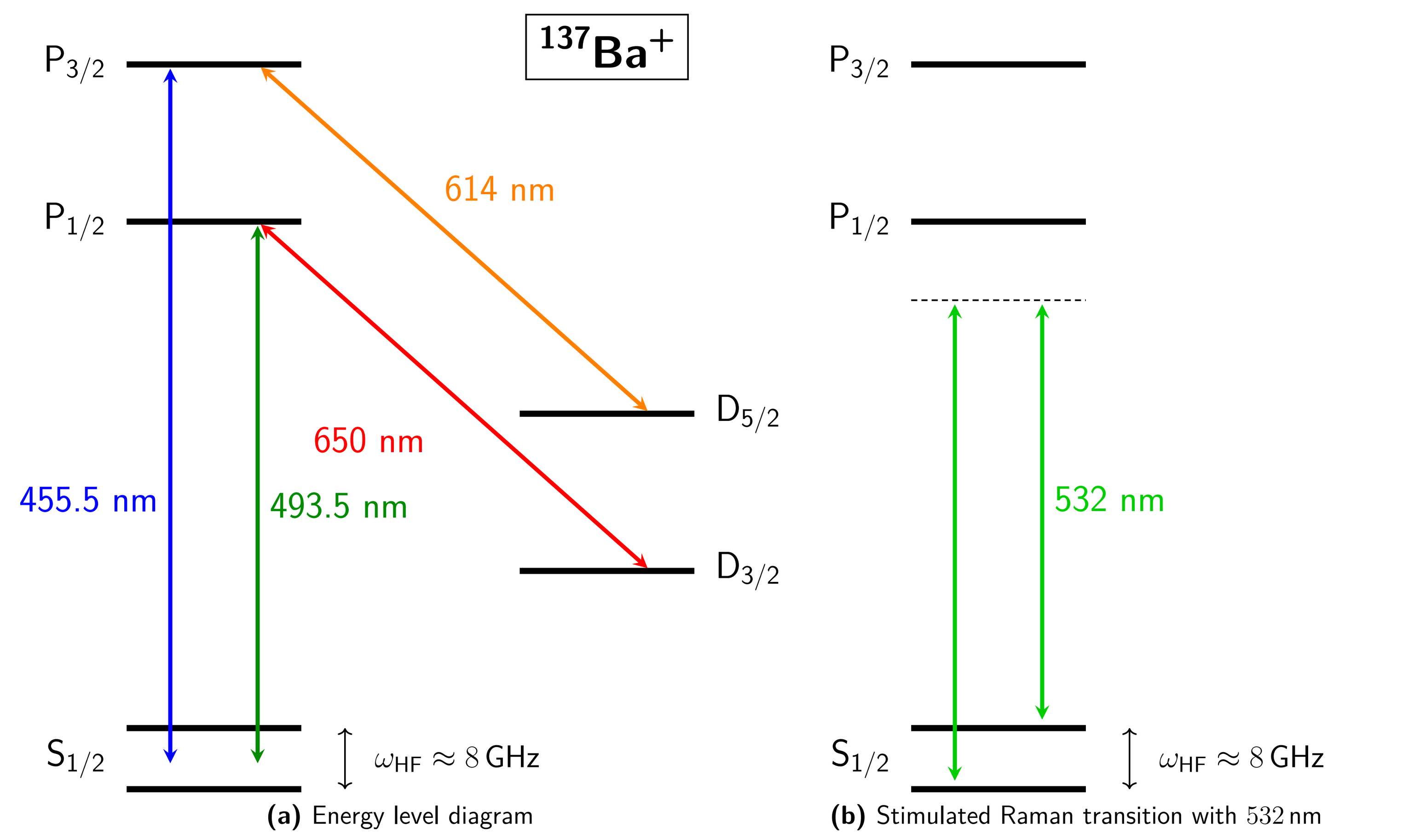

Figure 1. *(a) Energy level diagram of ^{137}Ba$^+$ showing the relevant electronic states and optical transitions with their corresponding wavelengths. (b) Schematic of energy levels relevant for the two-photon stimulated Raman transition scheme in ^{137}Ba$^+$ ion with $532\,$nm, showing the position of the virtual level.*

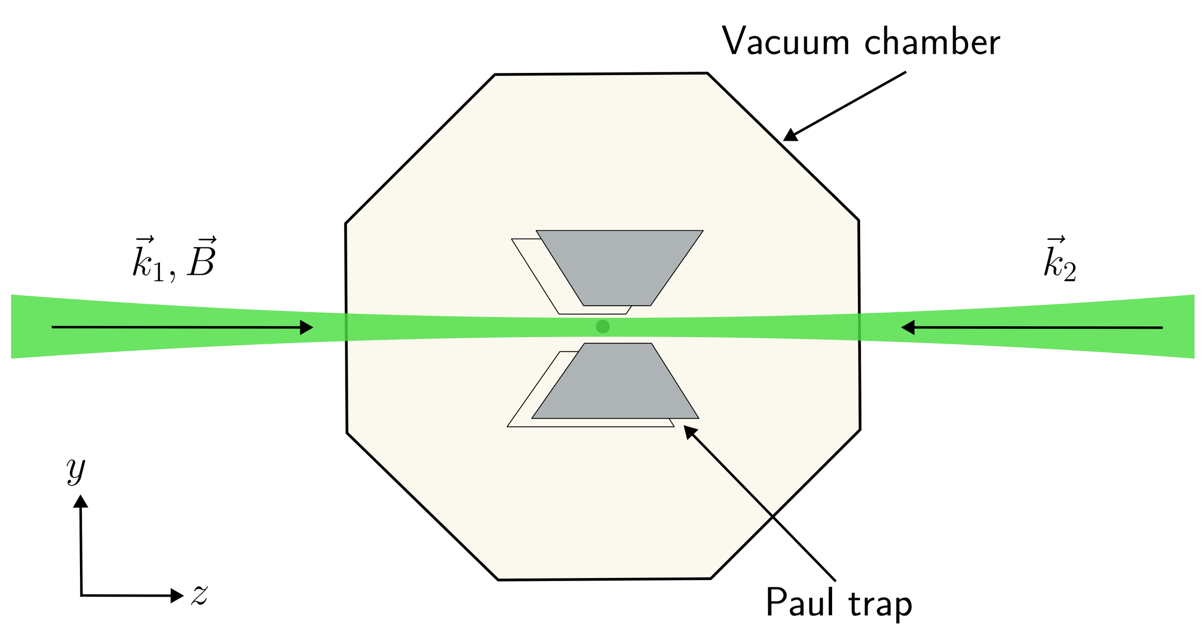

Figure 2. *We illustrate an example of the geometry formed by the pair of Raman lasers, typically at $532\,$nm, and the trap axes in the case of a trapped ^{137}Ba$^+$ ion in a linear Paul trap. The lasers propagate along the axis of the B-field ($\vec{k} \parallel \vec{B}$) and the axial trap axis $\hat{z}$, in this illustration. The allowed transitions in this geometry excludes π-transitions.*

Theoretical Minimum

1. The gate time t_Ω is inversely proportional to the Rabi frequency Ω.
2. The Rabi frequency Ω_R for a Raman transition is given as:

$$\Omega_R = \frac{e^{i(\phi_1-\phi_2)}}{4\hbar^2} \sum_k \frac{\langle \uparrow | \vec{d} \cdot \hat{\epsilon}_r E_r | k \rangle \langle k | \vec{d} \cdot \hat{\epsilon}_b E_b | \downarrow \rangle}{\omega_{ki} - \omega_l}, \tag{1}$$

   summed over P$_{1/2}$ and P$_{3/2}$, where for $\vec{E}_i = E_i \cos(\vec{k}_i \cdot \vec{r} - \omega_i t + \phi_i)\,\hat{\epsilon}_i, \quad i = \{r, b\}$.
3. The AC Stark shift (light shift) for the state $|i\rangle \equiv |n, L, S, J, I, F, m_F\rangle$ in the presence of a laser field is given by:

$$\Delta\omega_i = -\sum_k \frac{|\langle k | \vec{d} \cdot \vec{E} | i \rangle|^2}{4(\omega_{ki} - \omega_L)}, \\ = -\frac{3\pi c^2 I}{2\hbar} \sum_{k,q} C_{ki}^{(F,q)} \mu_{ki} \frac{1}{\omega_{ki} - \omega_L} \tag{2}$$

   where the coefficient $C_{ki}^{(F,q)}$ incorporates the angular momentum coupling for a given polarisation of light indexed by $q = \{-1, 0, +1\}$:

$$C_{ki}^{(F,q)} = (2F_k+1)(2F_i+1) \begin{Bmatrix} J_k & F_k & I \\ F_i & J_i & 1 \end{Bmatrix}^2 |\epsilon_q|^2 \begin{pmatrix} F_k & 1 & F_i \\ -m_{F_k} & q & m_{F_i} \end{pmatrix}^2 \tag{3}$$

   and we define $\mu_{ki} = \frac{(2J_k+1)A_{ki}}{\omega_{ki}^3}$ as the normalised transition strength.

Conclusion — Future Work — References

1. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis.
2. Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi.
3. Nulla malesuada porttitor diam.

- Matthew J. Boguslawski et al. "Raman Scattering Errors in Stimulated-Raman-Induced Logic Gates in ^{133}Ba$^+$". In: *Physical Review Letters* 131.6 (Aug. 2023), p. 063001. arXiv: 2212.02608 [quant-ph].
- I. D. Moore et al. "Photon Scattering Errors during Stimulated Raman Transitions in Trapped-Ion Qubits". In: *Phys. Rev. A* 107.3 (Mar. 2023), p. 032413. arXiv: 2211.00744 [quant-ph].
- P. Rosenbusch et al. "AC Stark Shift of the Cs Microwave Atomic Clock Transitions". In: *Physical Review A* 79.1 (Jan. 2009), p. 013404.
- Samuel R. Vizvary et al. "Eliminating Qubit-Type Cross-Talk in the omg Protocol". In: *Physical Review Letters* 132.26 (June 2024), p. 263201.
- D. J. Wineland et al. "Quantum Information Processing with Trapped Ions". In: *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361.1808 (July 2003), pp. 1349–1361.

Graphical Overview

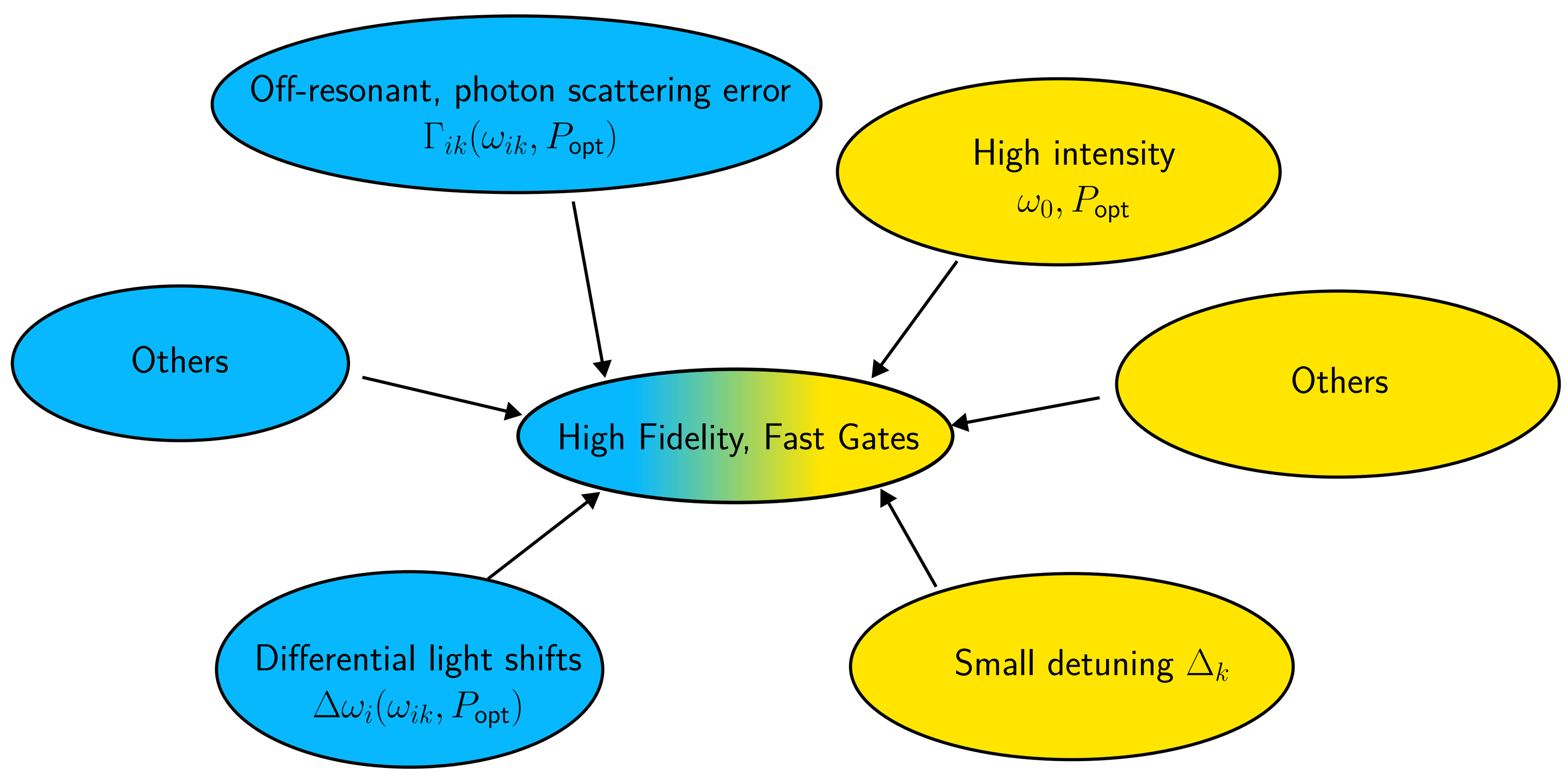

Figure 3. *Illustration of the various factors that affects the fidelity and duration of the gate operation. The factors affecting fidelity and gate duration are colour coded in blue and yellow. "Others" would refer to factors such as the fine structure splitting (which would differ between ion species), pulse shape, etc.*

Preliminary Results

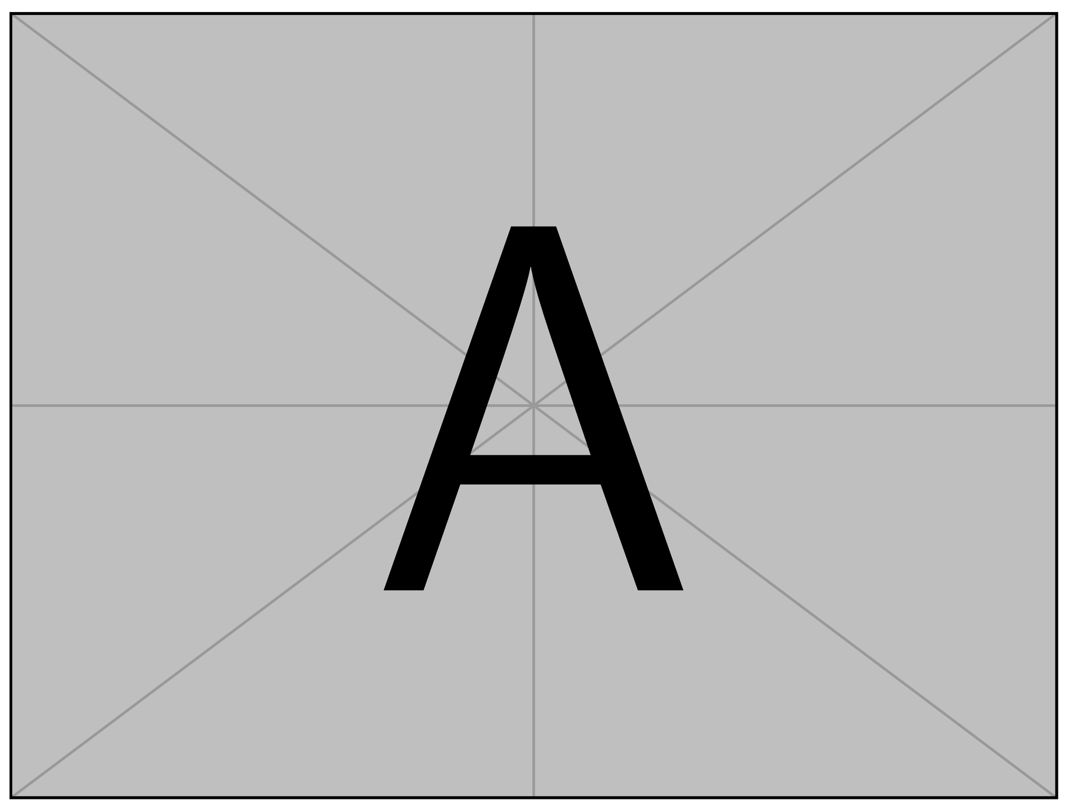

Figure 4. *Calculation of the Rabi frequency and the AC Stark shift against detuning Δ from the $P_{1/2}$ state, calculated assuming a beam waist of $20\,\mu$m and optical power of $30\,$mW for both beams in the pair.*

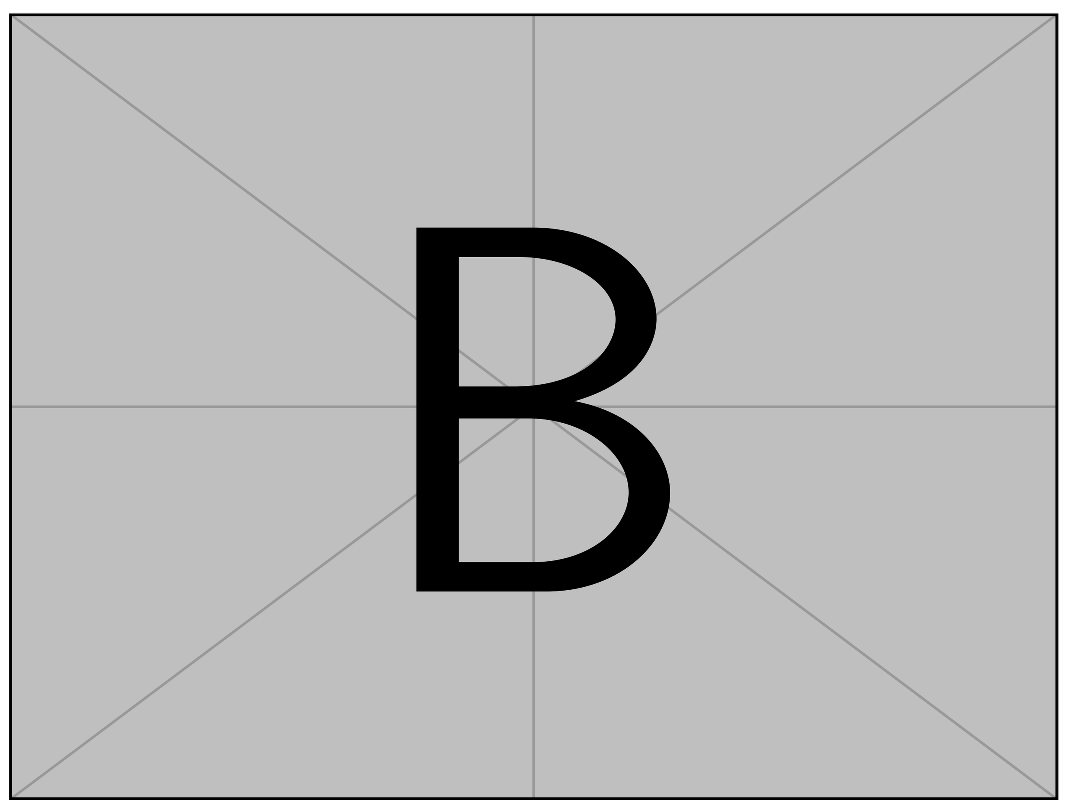

Figure 5. *Further, we quantify the error ϵ, in the gate fidelity $\mathcal{F}$, due to Stark shift as a consideration for determining an alternative laser frequency for addressing single-qubit Raman in ^{137}Ba$^+$.*

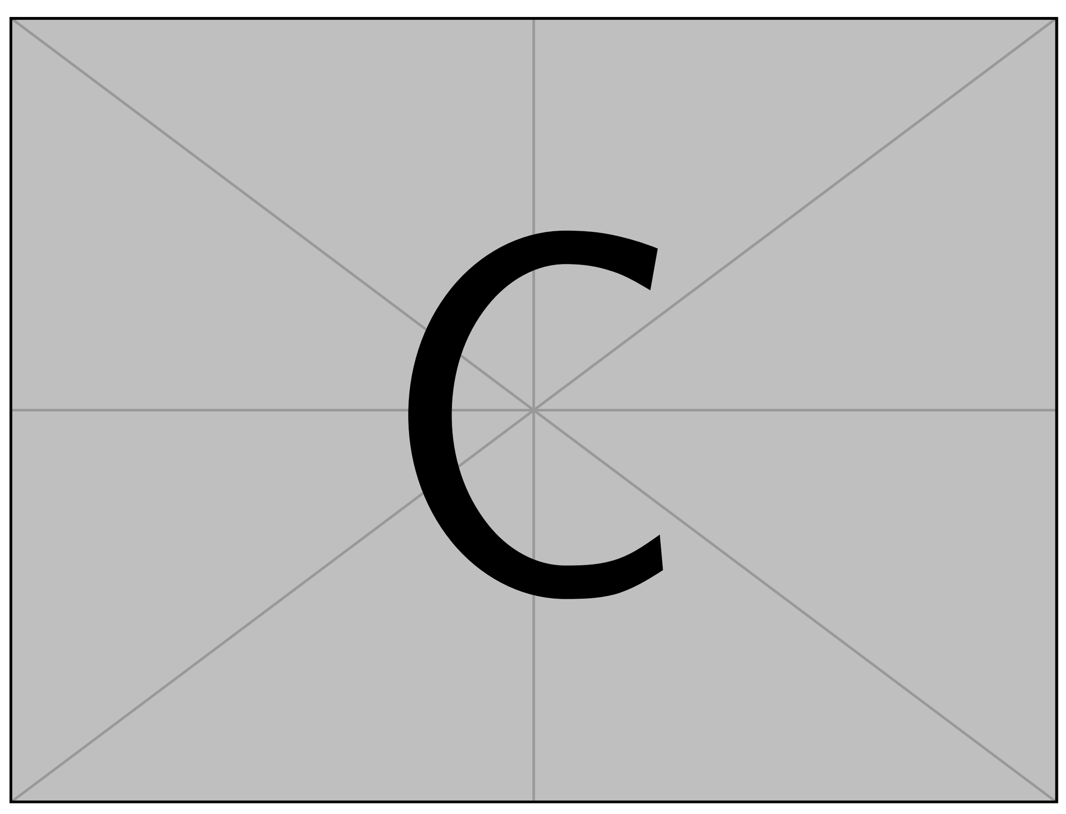

Figure 6. *Lastly, we calculate the gate error due to spontaneous photon scattering rate as a function of detuning.*