Modelling of two-photon Rydberg excitation of a single atom in optical tweezers

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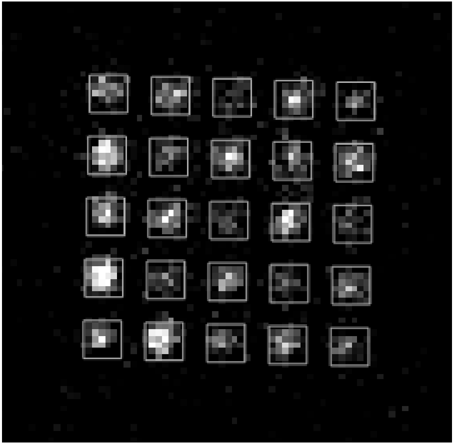
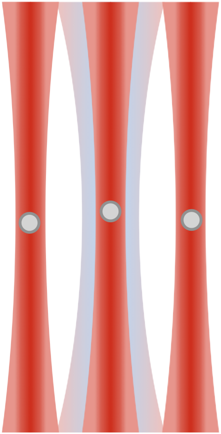
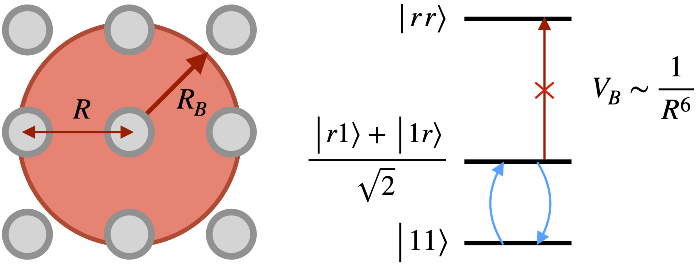
Quantum computer, arrays of neutral atoms





Two-qubit gates, Rydberg blockade

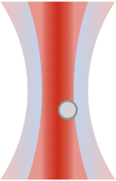
- Rydberg state ⇒ Strong dipole-dipole interaction ⇒ Two-qubit gates, entanglement



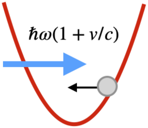
Rydberg excitation, decoherence

Decoherence $\Rightarrow$ Lower gate fidelities

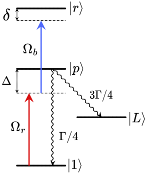
Atom dynamics in optical tweezers



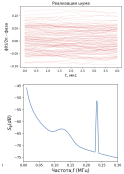
Doppler effect



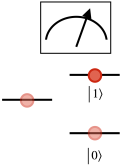
Intermediate state spontaneous decay



Laser phase noise



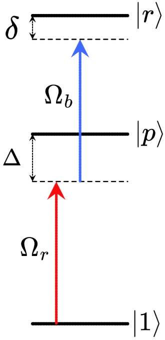
SPAM



Aim of the work: Modelling of two-photon Rydberg excitation error $\Rightarrow$ Optimization of experimental setup

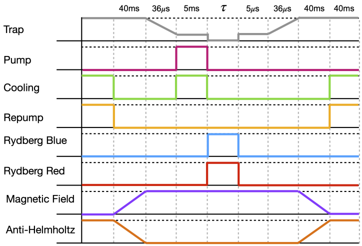
Two-photon excitation

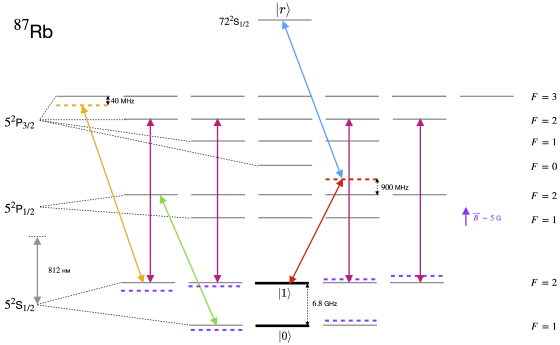
- Cascade scheme + 2 fields
- Effectively TLS with $\Omega = \frac{\Omega_r \Omega_b}{2\Delta} \sim E_1 E_2, \;\; \delta_{AC} = \frac{\Omega_b^2 - \Omega_r^2}{4\Delta}$



$$\hat{H} = -\Delta |p\rangle\langle p| - \delta |r\rangle\langle r| + \frac{\Omega_r}{2} |1\rangle\langle p| + \frac{\Omega_b}{2} |p\rangle\langle r| + h.c. \qquad (1)$$

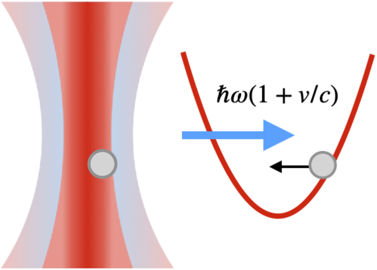
Pulse sequence





Decoherence due to atom dynamics

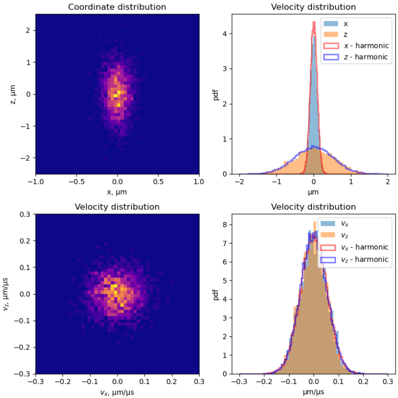
- $\Omega_i \sim E_i(x, y, z) \Rightarrow \Omega_i(t)$
- $\Delta = \Delta_0 + k_r v_z \Rightarrow \Delta(t)$
- $\delta = \Delta_0 + (k_r - k_b) v_z \Rightarrow \delta(t)$



$$\hat{H} = -\Delta(t)\hat{n}_p - \delta(t)\hat{n}_r + \frac{\Omega_r(t)}{2} |1\rangle \langle p| + \frac{\Omega_b(t)}{2} |p\rangle \langle r| + h.c. \quad (2)$$

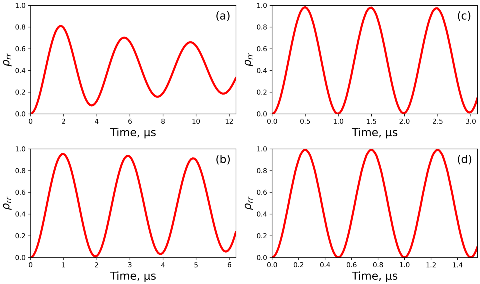
Sampling of atom in optical tweezers

Need atom trajectories in trap $\Rightarrow$ Monte-Carlo



Monte-Carlo $\Rightarrow \left(\vec{r}^{(i)}, \vec{v}^{(i)}\right) \Rightarrow (\vec{r}(t), \vec{v}(t)) \Rightarrow \Delta(t), \delta(t), \Omega_{r,b}(t)$

Decoherence, comparison to the literature



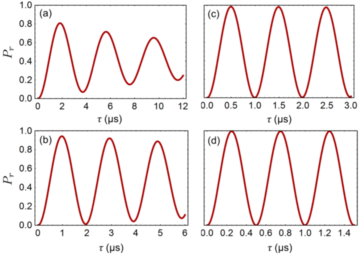
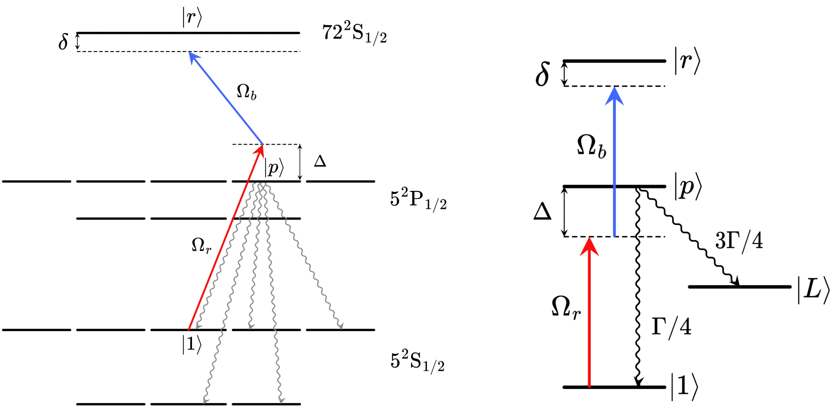


FIG. 5. Influence of the Doppler effect on the Rabi oscillations for a temperature of $T = 30\ \mu$K and Rabi frequencies $\Omega/(2\pi)$ of (a) 250 kHz, (b) 500 kHz, (c) 1 MHz, and (d) 2 MHz.

[1] Sylvain de Léséleuc, et al., Analysis of imperfections in the coherent optical excitation of single atoms to Rydberg states, Phys. Rev. A 97, 053803 (2018)

Atomic levels, spontaneous decay



Spontaneous decay

Master equation

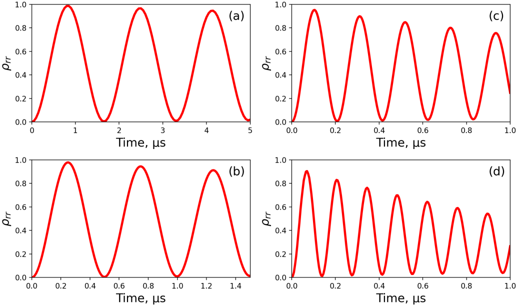
$$\dot{\rho} = -i[H,\rho] + \sum_i \left(J_i \rho J_i^\dagger - \frac{1}{2} J_i^\dagger J_i \rho - \frac{1}{2} \rho J_i^\dagger J_i \right), \tag{3}$$

Hamiltonian and jump operators

$$H = -\Delta \hat{n}_p - \delta \hat{n}_r + \frac{\Omega_r}{2} |1\rangle \langle p| + \frac{\Omega_b}{2} |p\rangle \langle r| + h.c. \tag{4}$$

$$J_1 = \sqrt{\Gamma/4}\, |1\rangle \langle p| \, , \; J_L = \sqrt{3\Gamma/4}\, |L\rangle \langle p| \tag{5}$$

Decay, comparison to the literature



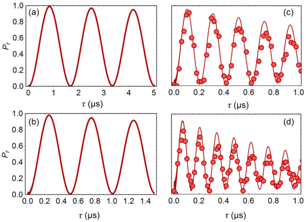
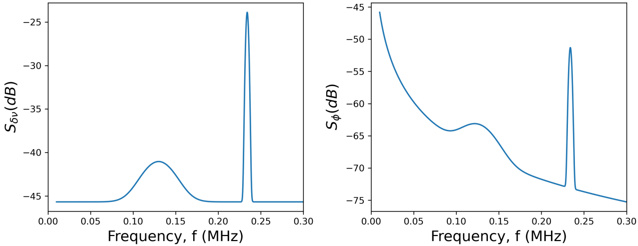


FIG. 6. Influence of the spontaneous emission from $|p\rangle$. (a) and (b) Calculated Rabi oscillation obtained by solving the OBEs for (a) $\Delta = 2\pi \times 740$, $\Omega_b = 2\pi \times 30$, and $\Omega_r/(2\pi) = 30$ MHz and (b) 100 MHz. (c) and (d) Comparison between the simulation and the experimental data (with $n = 61$) for fixed $\Omega_b = 2\pi \times 35$ and $\Omega_r = 2\pi \times 210$ MHz but for decreasing values of the intermediate-state detuning: (c) $\Delta = 2\pi \times 740$ MHz and (d) $\Delta = 2\pi \times 477$ MHz.

[1] Sylvain de Léséleuc, et al., Analysis of imperfections in the coherent optical excitation of single atoms to Rydberg states, Phys. Rev. A 97, 053803 (2018)

Laser phase noise, decoherence

- Laser phase noise $\Rightarrow \Omega_i(t) = |\Omega_i(t)|e^{i\phi_i(t)}$
- Laser frequency stabilization by ULE-resonator $\Rightarrow$ Servobumps
- Laser frequency noise = White noise + Servobumps



Laser phase noise spectrum with parameters from [2]

[2] X. Jiang, et al., Sensitivity of quantum gate fidelity to laser phase and intensity noise, Phys. Rev. A 107, 042611 (2023)

Sampling of phase noise

Spectral density of frequency noise

$$S_{\delta\nu}(f) = h_0 + h_g \exp\left(-\frac{(f-f_g)^2}{2\sigma_g^2}\right) + h_g \exp\left(-\frac{(f+f_g)^2}{2\sigma_g^2}\right) \quad (6)$$

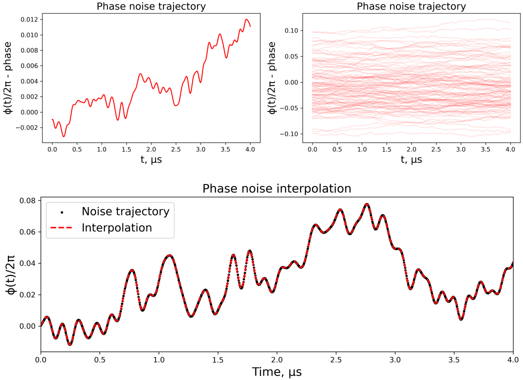
Spectral density of phase noise

$$S_\phi(f) = S_{\delta\nu}(f)/f^2 \quad (7)$$

Sampling of noise trajectories

$$\phi(t) = \sum_{i=1}^{N} 2\sqrt{S_\phi(f_i)\Delta f}\cos\left(2\pi f_i t + \phi_i\right), \quad \phi_i \sim U[0, 2\pi] \quad (8)$$

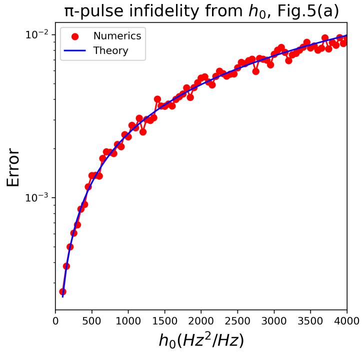
Realizations of noise trajectories



Phase noise trajectories with parameters from [2] and interpolation

[2] X. Jiang, et al., Sensitivity of quantum gate fidelity to laser phase and intensity noise Phys. Rev. A 107, 042611 (2023)

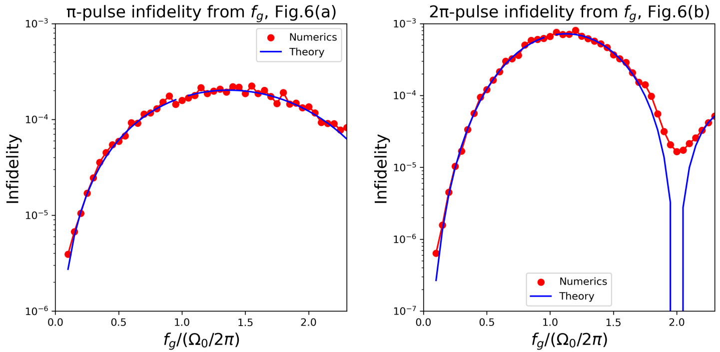
Comparison to the literature in one-photon scheme



Infidelity of $\pi-$ и $2\pi-$ pulses from white noise spectral density.

[2] X. Jiang, et al., Sensitivity of quantum gate fidelity to laser phase and intensity noise Phys. Rev. A 107, 042611 (2023)

Comparison to the literature in one-photon scheme



Infidelity of $\pi-$ и $2\pi-$ pulses from servobump frequency.

[2] X. Jiang, et al., Sensitivity of quantum gate fidelity to laser phase and intensity noise, Phys. Rev. A 107, 042611 (2023)

State preparation and measurement errors

- η - state preparation error

  Finite efficiency of optical pumping to $|1\rangle$ $\Rightarrow$ Non-zero population of other $5^2\mathrm{S}_{1/2}$ hyperfine and magnetic sublevels

- ε - false-positive detection error

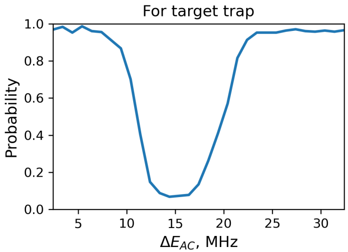
  Nonideal vacuum, shorter lifetime due to fluorescence, shift during time trap is turned off $\Rightarrow$ atom loss not because of $|r\rangle$

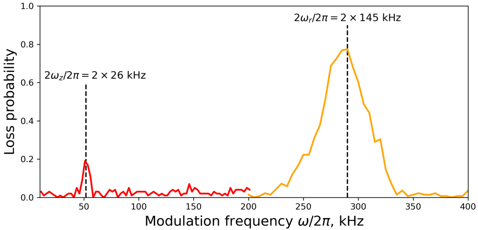
- ε' - false-negative detection error

  Finite lifetime of $|r\rangle$ $\Rightarrow$ Deexcitation, no atom loss

Trap parameters

- Stark shift from trap $\Rightarrow U_0 = \Delta E_{AC}$
- Parametric heating $\Rightarrow \omega_r, \omega_z \Rightarrow w_0,\ z_0$

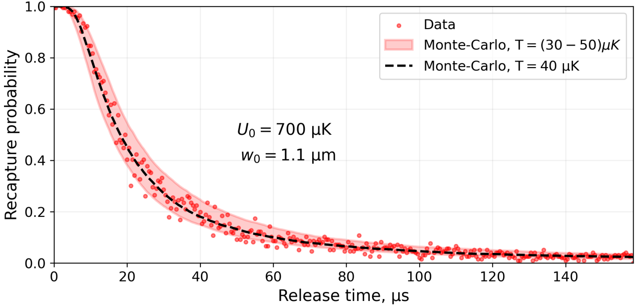




Results: $w_0 = 1.1\ \mu$m, $z_0 = 4.2\ \mu$m, $U_0 = 700\ \mu$K

Atom temperature

- Release&recapture $\Rightarrow$ Atom temperature T



Results: $T = 40\ \mu$K

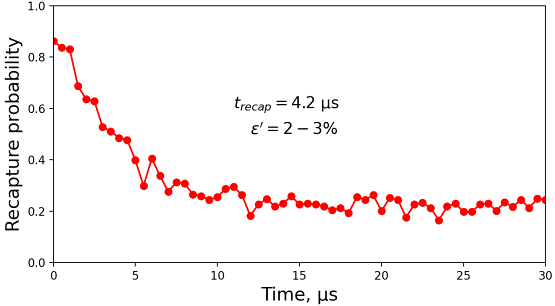
Excitation beams parameters

- Wavelength meter
  $\Rightarrow \Delta = 0.9$ GHz, $\lambda_r = 795$ nm, $\lambda_b = 474$ nm
- δ is experimentally tuned to reach two-photon resonance
- Distance between sites $3.6\ \mu$m + Scan of blue laser position between sites $\Rightarrow\ w_b = 3.0\ \mu$m
- Camera $\Rightarrow\ w_r = 10.0\ \mu$m
- Intensity of blue laser $\Rightarrow \Omega_b = 2\pi \times 60$ MHz
- $\Omega_b,\ \Omega \Rightarrow \Omega_r = 2\pi \times 60$ MHz

Estimation of ε' error

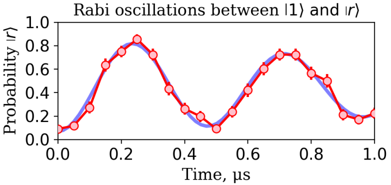
Release&recapture for atom in $|r\rangle$ with antitrapping $\Rightarrow \varepsilon'$ [1]

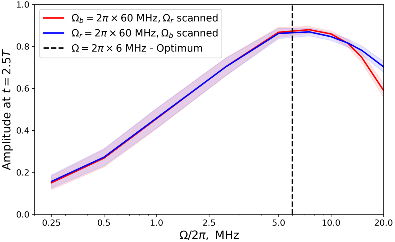
$$\varepsilon' = \Gamma_R t_{recap} \simeq 2 - 3\% \text{ [1]}, \;\; 1/\Gamma_R \simeq 160 \; \mu s \text{ [3]} \tag{9}$$



Release&recapture for atom in $|r\rangle$ with antitrapping

Preliminary measurements and optimal parameters





Up: Preliminary measurements and comparison with model.
Down: Two-photon Rabi frequency scan and optimum.

Results:

- Model of two-photon Rydberg excitation of single atom in optical tweezers is implemented. Model accounts for atom dynamics, intermediate state spontaneous decay, laser phase noise and SPAM. Results are compared with [1] and [2].
- Optical trap depth and geometrical sizes, atom temperature, excitation beam detunings and one-photon Rabi frequencies are measured.
- Model makes it possible to find optimal parameters of two-photon Rydberg excitation in our experiment.
- Measurements of laser phase noise and SPAM-errors are in progress.

[1] Sylvain de Léséleuc, et al., Analysis of imperfections in the coherent optical excitation of single atoms to Rydberg states, Phys. Rev. A 97, 053803 (2018)
[2] X. Jiang, et al., Sensitivity of quantum gate fidelity to laser phase and intensity noise, Phys. Rev. A 107, 042611 (2023)

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Gaussian beam

$$E = E_0 \left(\frac{w(z)}{w_0} \right) \exp\left(-\frac{x^2 + y^2}{w(z)^2} \right) \exp\left(-i\phi(z) \right), \tag{10}$$

$$w(z) = w_0 \sqrt{1 + (z/z_0)^2}, \quad z_0 = \frac{\pi w_0^2}{\lambda}, \tag{11}$$

$$R(z) = z \left[1 + \left(\frac{z_0}{z} \right)^2 \right], \quad \psi(z) = \arctan\left(\frac{z}{z_0} \right). \tag{12}$$

$$\phi(z) = kz + k \frac{r^2}{2R(z)} - \psi(z), \tag{13}$$

Atom trajectories

Monte-Carlo ⇒ Initial conditions $(x^{(i)}, y^{(i)}, z^{(i)}, v_x^{(i)}, v_y^{(i)}, v_z^{(i)})$

- $x(t) = x^{(i)} \cos(\omega_r t) + \frac{v_x^{(i)}}{\omega_r} \sin(\omega_r t)$,
- $y(t) = y^{(i)} \cos(\omega_r t) + \frac{v_y^{(i)}}{\omega_r} \sin(\omega_r t)$,
- $z(t) = z^{(i)} \cos(\omega_z t) + \frac{v_z^{(i)}}{\omega_z} \sin(\omega_z t)$.

Sampling of atom in optical tweezers

Metropolis-Hastings algorithm

Proposal distribution

$$(d\vec{r}, d\vec{v}) \sim \mathcal{N}(0, \Sigma), \quad \Sigma = \frac{kT}{m}\text{diag}\left(\frac{1}{\omega_r^2}, \frac{1}{\omega_r^2}, \frac{1}{\omega_z^2}, 1, 1, 1\right) \tag{14}$$

On each step we **suggest** shift from the current point

$$(\vec{r}^*, \vec{v}^*) = \left(\vec{r}^{(i)} + d\vec{r}, \vec{v}^{(i)} + d\vec{v}\right) \tag{15}$$

Than we accept new point with probability p($\sim$ Boltzman)

$$p = \min\left\{\exp\left(-\frac{E\left(\vec{r}^*, \vec{v}^*\right)}{E\left(\vec{r}^{(i)}, \vec{v}^{(i)}\right)}\right), 1\right\} \tag{16}$$

Laser phase noise parameters and и theory from [2]

- $h_0 = 13.0 \cdot 10^{-6}$ MHz^2/MHz
- $h_{g1} = 25.0 \cdot 10^{-6}$ MHz^2/MHz,
  $h_{g2} = 2000.0 \cdot 10^{-6}$ MHz^2/MHz
- $f_{g1} = 130.0 \cdot 10^{-3}$ MHz, $f_{g2} = 234.0 \cdot 10^{-3}$ MHz
- $\sigma_{g1} = 18.0 \cdot 10^{-3}$ MHz, $\sigma_{g2} = 1.5 \cdot 10^{-3}$ MHz

Infidelity of one-photon excitation due to white noise

$$\varepsilon = \frac{\pi^3 h_0 N}{\Omega}. \tag{17}$$

Infidelity of one-photon excitation due to servobump

$$\varepsilon = 2 s_g (\pi f_g \Omega_0)^2 \frac{1 - (-1)^{2N} \cos\left(4\pi^2 N f_g / \Omega\right)}{(\Omega^2 - 4\pi^2 f_g^2)^2}. \tag{18}$$

N - number of π-pulses

SPAM-errors

$\tilde{P}_1$, $\tilde{P}_r$ - probabilities to be in $|1\rangle$, $|r\rangle$ without SPAM-errors,
P_1, P_r - probabilities to be in $|1\rangle$, $|r\rangle$ with SPAM-errors [1]

$$P_1 = \eta(1-\varepsilon) + (1-\eta)(1-\varepsilon)\left[\tilde{P}_1 + \varepsilon'\tilde{P}_r\right], \tag{19}$$

$$P_r = \eta\varepsilon + (1-\eta)\left[\varepsilon\tilde{P}_1 + (1-\varepsilon'+\varepsilon\varepsilon')\tilde{P}_r\right]. \tag{20}$$

[1] Sylvain de Léséleuc, et al., Analysis of imperfections in the coherent optical excitation of single atoms to Rydberg states, Phys. Rev. A 97, 053803 (2018)