Composite Biased Rotations for Precise Raman Control of Spinor Matterwaves

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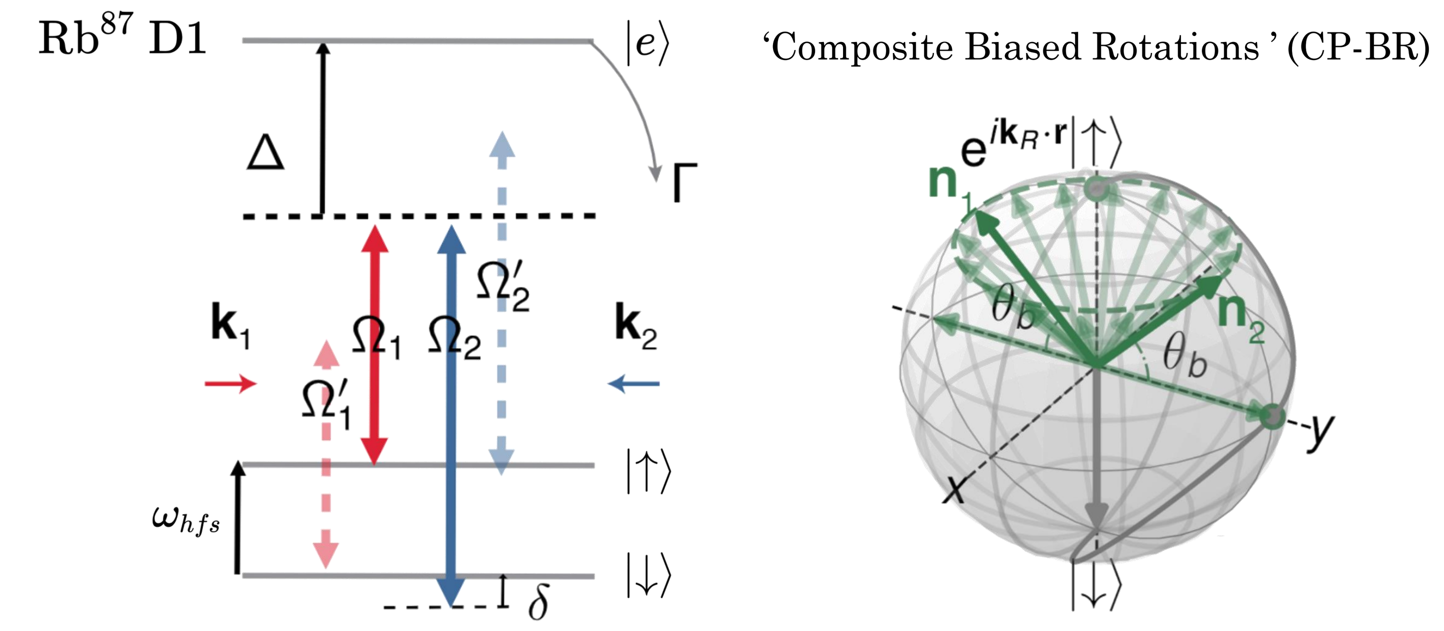
I. Introduction

Precise control of hyperfine matterwaves via Raman excitations is instrumental to a class of atom-based quantum technology. We drive an intermediate single-photon detuning ($\Delta \approx 4\omega_{hfs}$), where rotations of atomic spinors are biased by substantial light shifts. Taking advantage of the fixed bias angle, we demonstrate numerically and experimentally that composite biased rotations can be optimized to enable precise ensemble spinor matterwave control within nanoseconds. According to the latest results, we have achieved gate fidelity exceeding 99.2% with pulses duration time in a few tens of nanoseconds (~64ns).

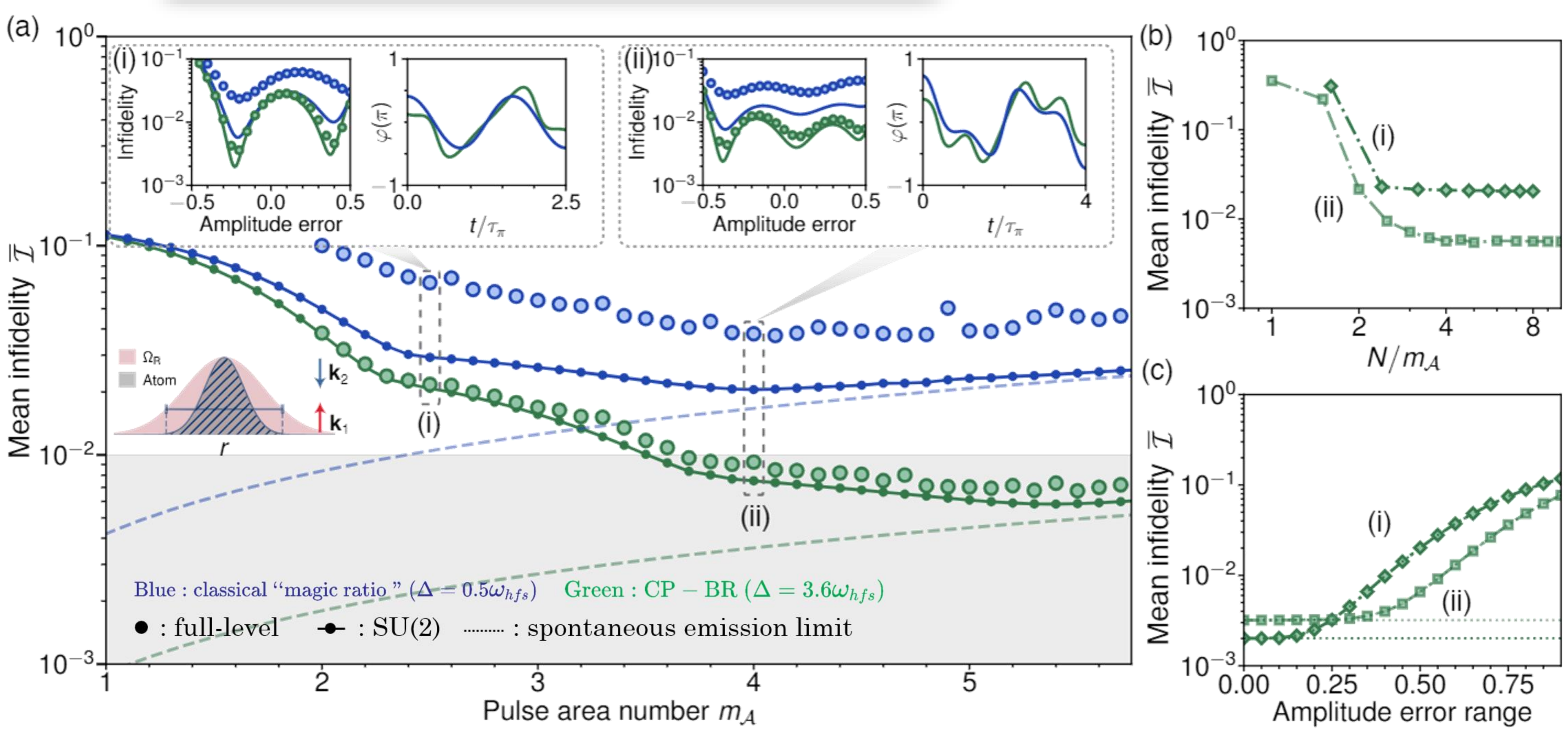


II. Theoretical Model[1]

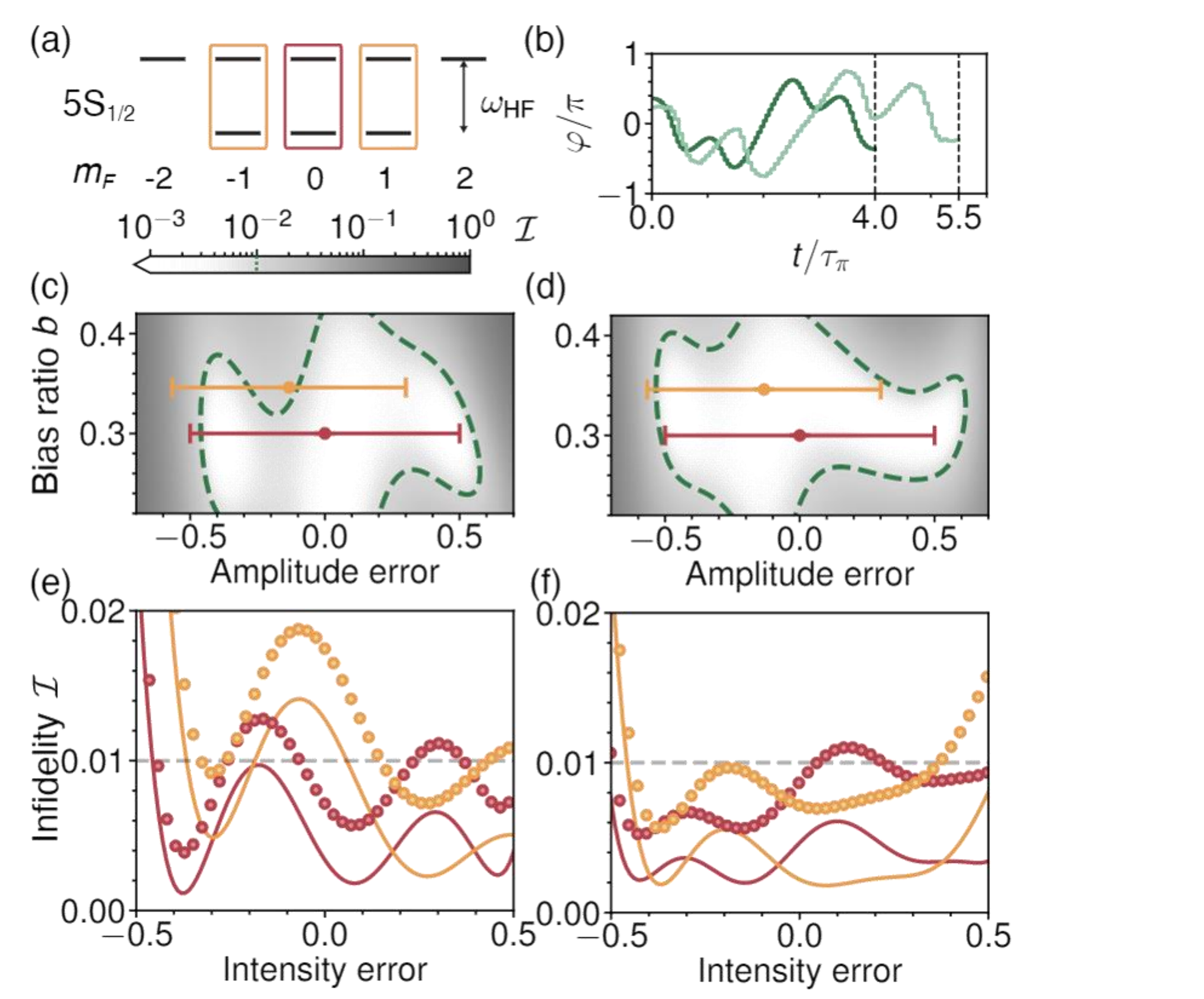
$$H = -\frac{1}{2}\hbar\delta\sigma_z + \frac{1}{2}\hbar|\Omega_R|(\sigma_x\cos\varphi + \sigma_y\sin\varphi)$$

$$\delta = \frac{|\Omega_1|^2}{4\Delta} + \frac{|\Omega_2'|^2}{4(\Delta-\omega_{HF})} - \frac{|\Omega_2|^2}{4\Delta} - \frac{|\Omega_1'|^2}{4(\Delta+\omega_{HF})}$$

$$\theta_b = \tan^{-1}(\delta/|\Omega_R|)$$



- Multiple Zeeman-spins



Theoretical calculations indicate that high-fidelity matterwave control for different Zeeman spinors can be realized in parallel.

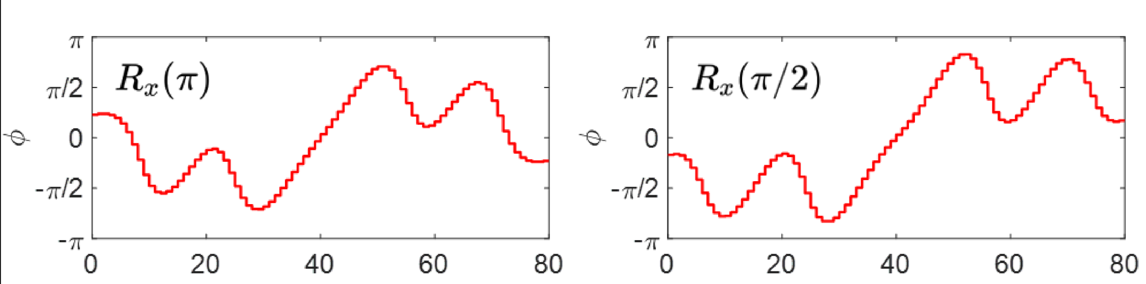
III. Pulse shaping[1]

- Optimization algorithm-**GRAPE**

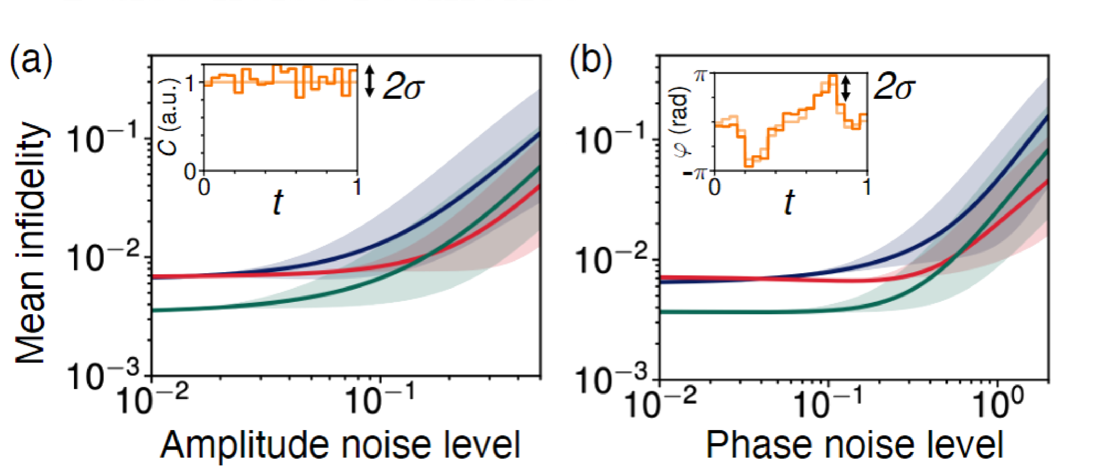
SU(2) rotation operator: $U(\mathcal{A}, b, \varphi) = 1\cos\frac{\tilde{\phi}}{2} - i\sin\frac{\tilde{\phi}}{2}\frac{\sigma_x\cos\varphi + \sigma_y\sin\varphi + b\sigma_z}{\sqrt{1+b^2}}$

Gate fidelity: $\mathcal{F} = \frac{1}{6}\sum_{j=1}^{6}|\langle\psi_j|U^\dagger\tilde{U}|\psi_j\rangle|^2$

Gradient: $g_i = -\frac{\partial\mathcal{F}}{\partial\tilde{U}}\frac{\partial\tilde{U}}{\partial\varphi_i}$ $\frac{\partial\tilde{U}}{\partial\varphi_i} = \tilde{U}_N\cdots\tilde{U}_{i+1}\frac{\partial\tilde{U}_i}{\partial\varphi_i}\tilde{U}_{i-1}\cdots\tilde{U}_1$



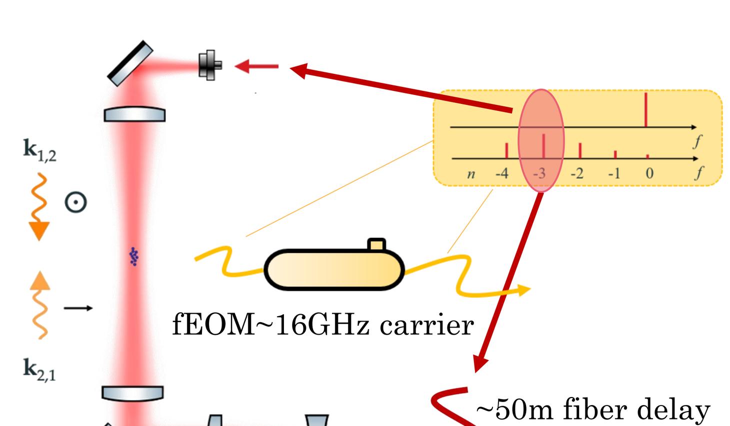
- Pulse noise resilience

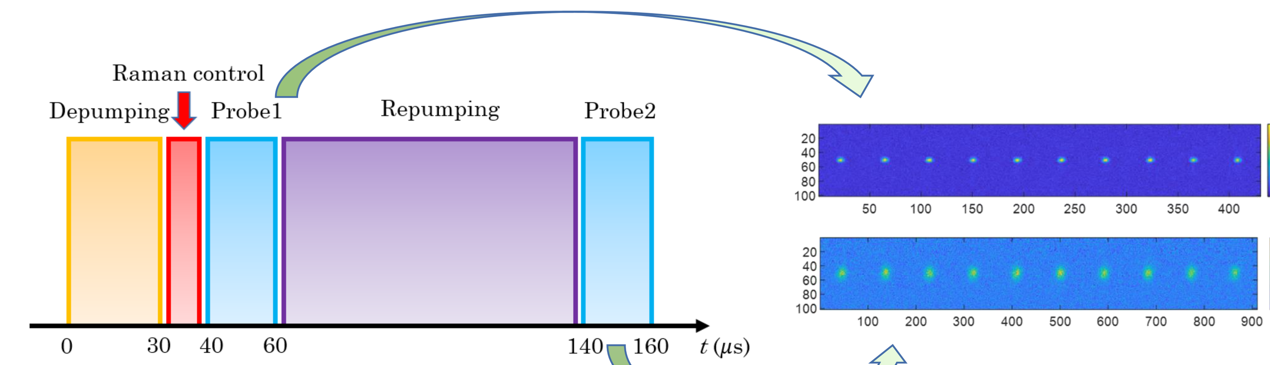


Blue: N = 20, A = 4π, Red: N = 80, A= 4 π, Green: N= 80,A = 5.5π

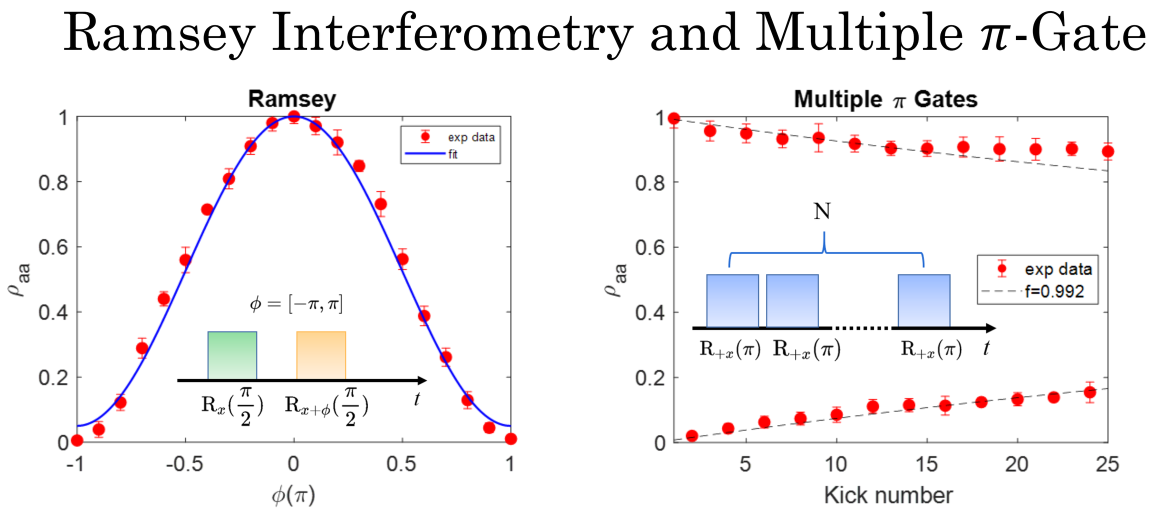
IV. Experimental setup and results

- The experimental setup and measurement procedure

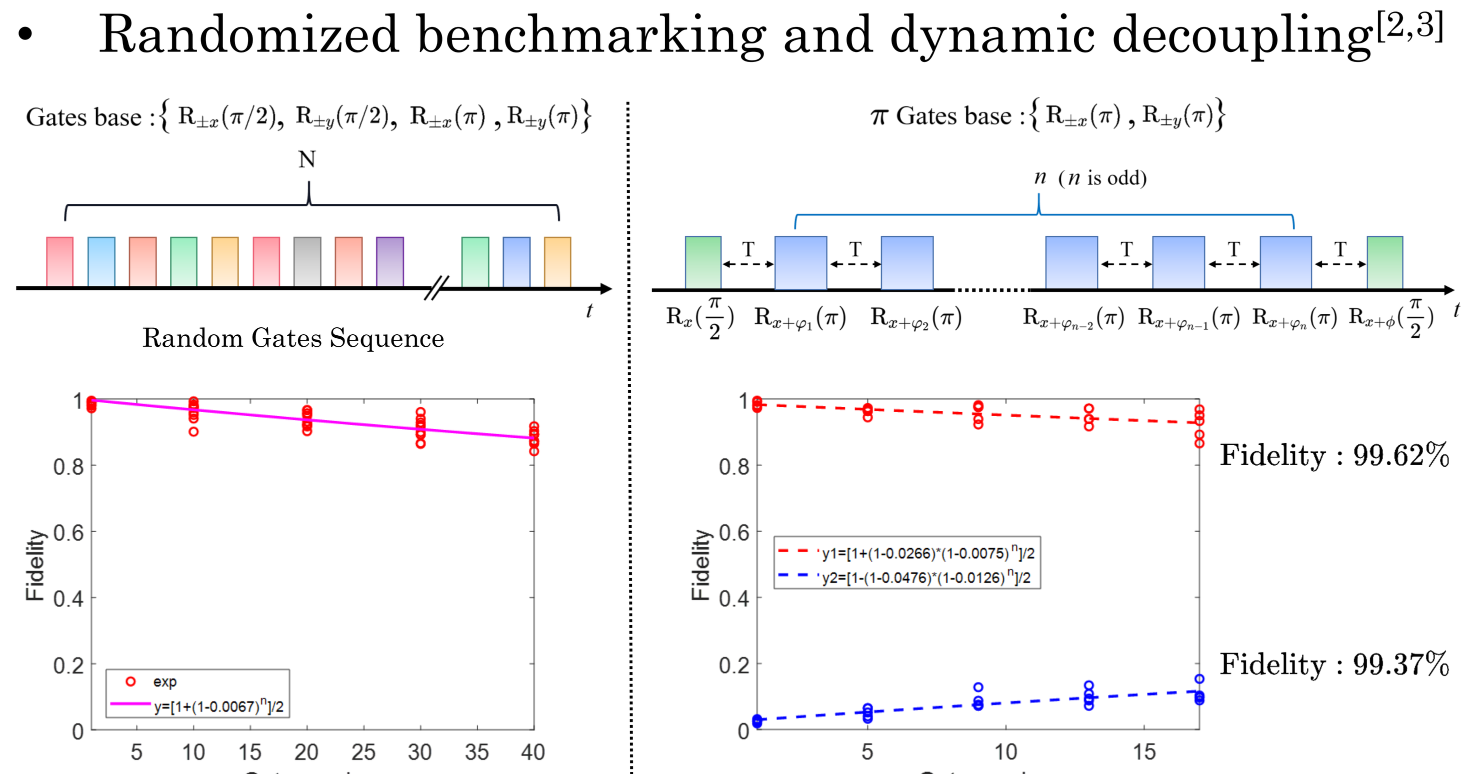




- Ramsey Interferometry and Multiple π-Gate

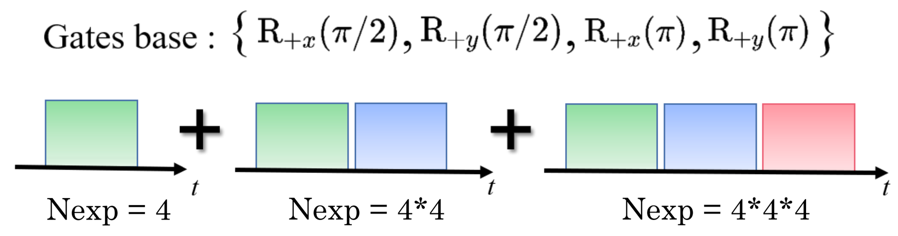


- Randomized benchmarking and dynamic decoupling[2,3]

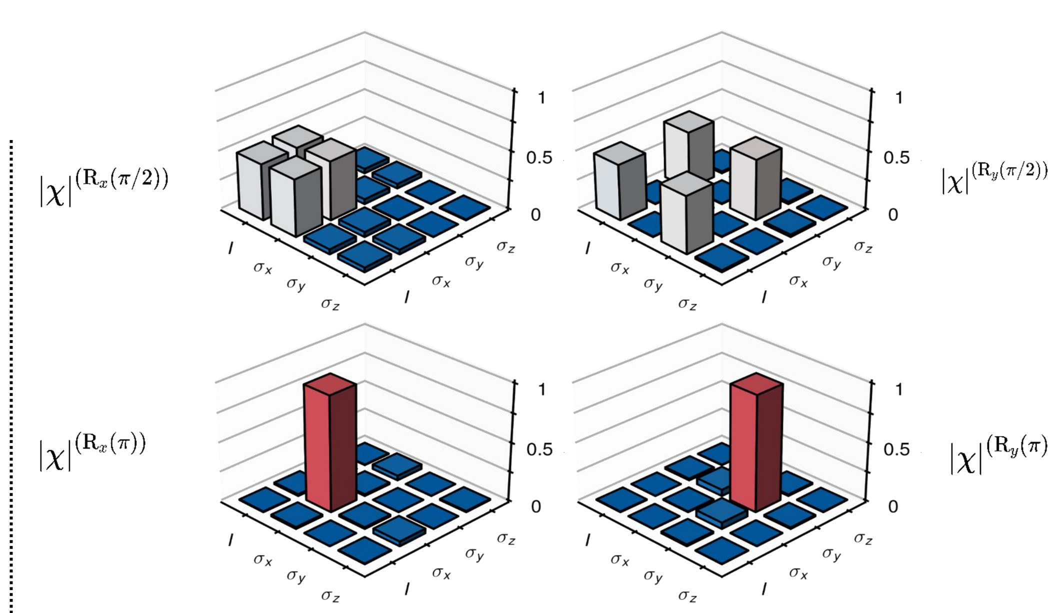


- Quantum process tomography

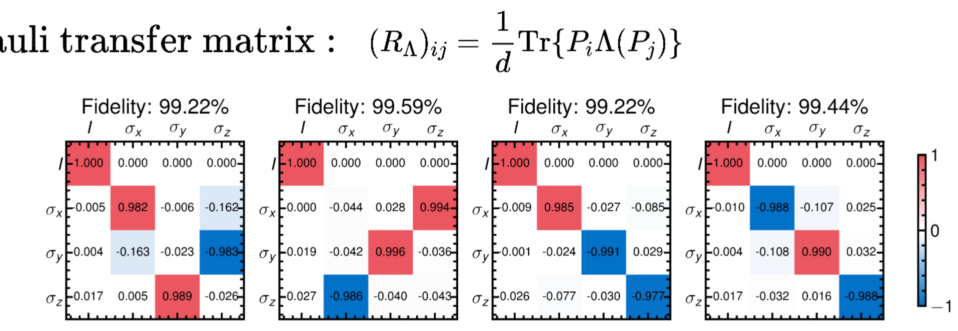
Gates base : $\{R_{+x}(\pi/2), R_{+y}(\pi/2), R_{+x}(\pi), R_{+y}(\pi)\}$



Gate χ – matrix : $\Lambda(\rho) = \sum_{j,k=1}^{d^2}\chi_{jk}P_j\rho P_k$ $P_j \in \mathcal{P}^{\otimes n}, \mathcal{P} = \{I, \sigma_x, \sigma_y, \sigma_z\}$



Pauli transfer matrix : $(R_\Lambda)_{ij} = \frac{1}{d}\mathrm{Tr}\{P_i\Lambda(P_j)\}$



V. conclusion

We propose the composite biased rotation method supports a suitable single photon detuning Δ to balance the optical power efficiency with the requirements on the control speed and/or the suppression of excited-state dynamics. Now we have achieved exceeding 99.2% Gates operation efficiency in our latest experimental results. This lays out the foundation for our next step for realizing practically useful large momentum transfer in Raman atom interferometry.

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VI. Reference

[1] QIU L, YUAN H, WU S. PHYSICAL REVIEW RESEARCH 5, 043094 (2023) High-fidelity Raman matterwave control by composite biased rotations[J].
[2] OLMSCHENK S, CHICIREANU R, NELSON K D, et al. Randomized benchmarking of atomic qubits in an optical lattice[J/OL]. New Journal of Physics, 2010: 113007.
[3] KNILL E, LEIBFRIED D, REICHLE R, et al. Randomized Benchmarking of Quantum Gates[J].