

Engineering Bell States in Atom-Molecule Condensates

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Motivation

Macroscopic many-body superpositions encapsulate quantum entanglement and can be utilized for quantum sensing, interferometry, and logical-qubit encoding. We aim to engineer the maximally entangled Bell state

$$|\Psi_{\text{Bell}}\rangle = \frac{|0, N\rangle + e^{i\phi} |N/2, 0\rangle}{\sqrt{2}},$$

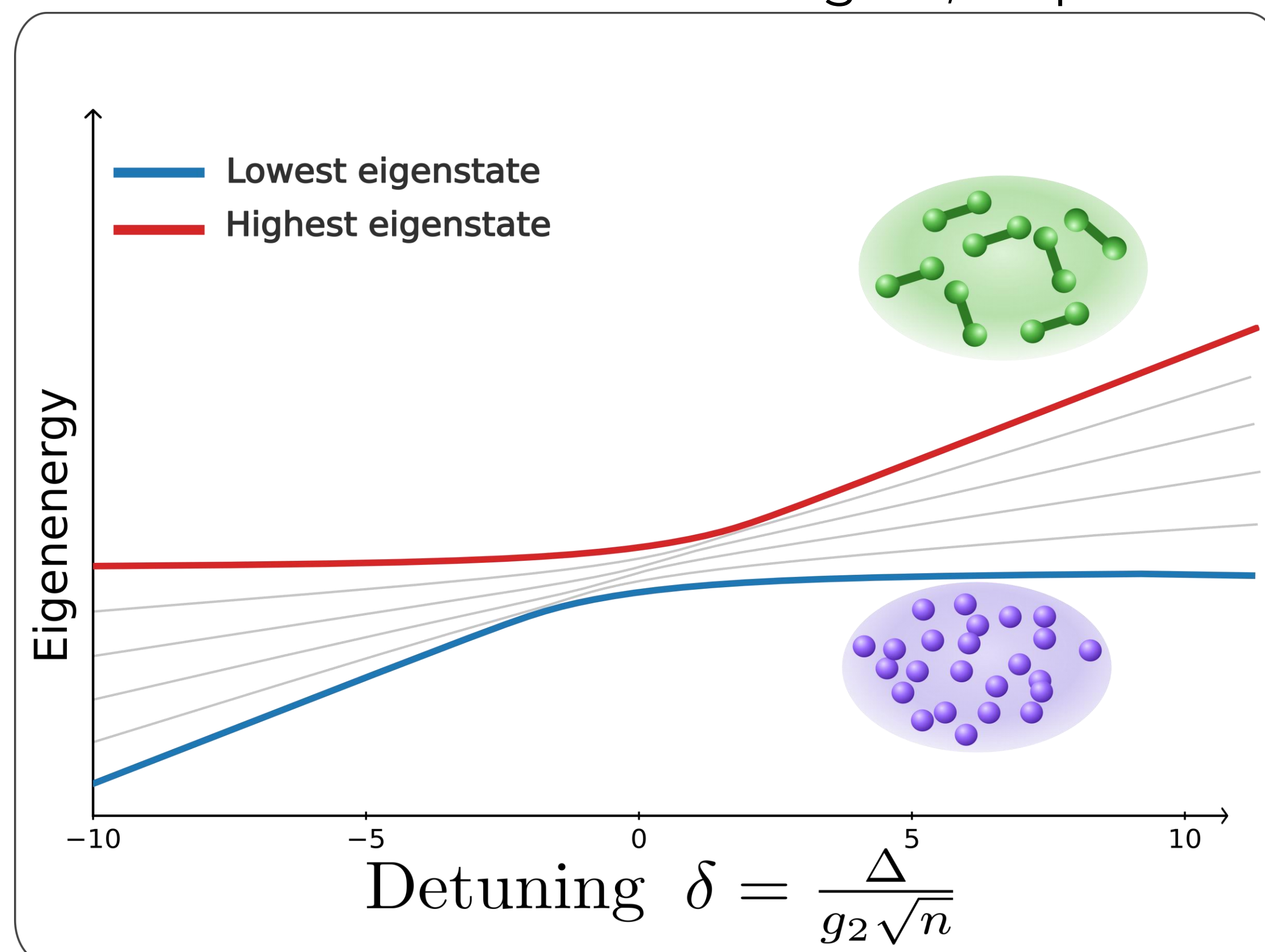
combining the all-atom and all-molecule configurations. The ensuing atom-molecule features a finite ladder of many-body states, offering a controllable pathway for generating entangled states.

Atom-Molecule Mixture

Ultracold molecular condensates (mBECs) provide fertile experimental platforms for quantum computing and ultracold chemistry. Strikingly, a pair of atoms can be coherently converted into diatomic molecules using magnetic field controlled detuning Δ . The mBEC Hamiltonian reads

$$\hat{H} = \Delta \hat{b}^\dagger \hat{b} + g_2 (\hat{b}^\dagger \hat{a}^2 + \hat{a}^{\dagger 2} \hat{b}) + g_{AA} \hat{a}^{\dagger 2} \hat{a}^2 + g_{MM} \hat{b}^{\dagger 2} \hat{b}^2.$$

g_2 is the coherent Feshbach coupling, g_{AA} and g_{MM} are atom-atom and molecule-molecule strengths, respectively.



Energy spectrum showcasing that at large molecular detunings, the lowest and highest eigenstates refer to all-atom and all-molecule populations, respectively.

Quantum state engineering

Detuning modulation

$$\delta(t) = \delta_0 + A_j \cos(\omega_j t + \phi_j),$$

with resonant driving frequency

$$\omega_j = E_{j+1} - E_j.$$

Rabi frequency

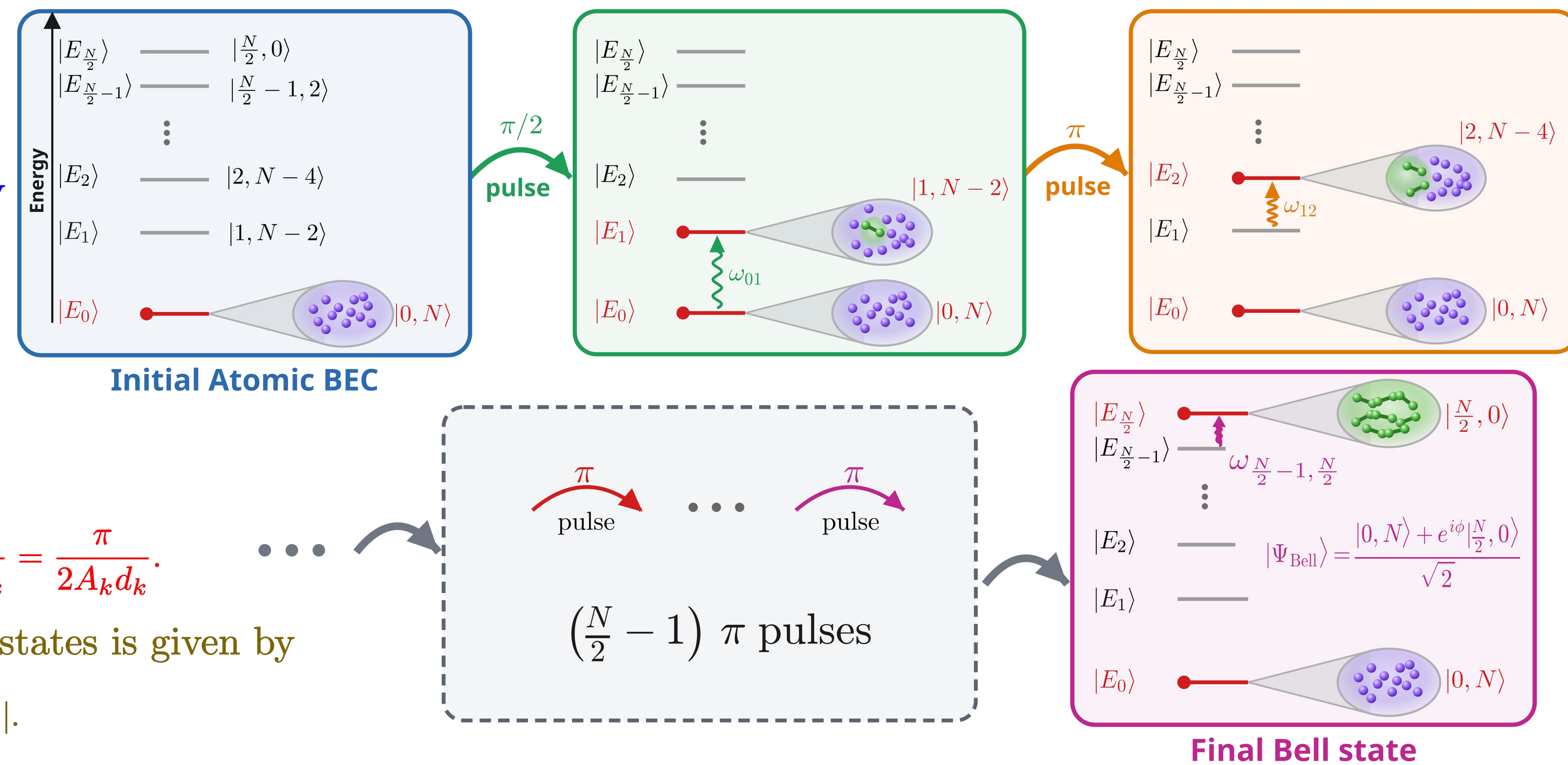
$$\Omega_k = A_k |\langle E_{k+1} | \hat{n}_m | E_k \rangle| = A_k d_k.$$

The pulse durations are

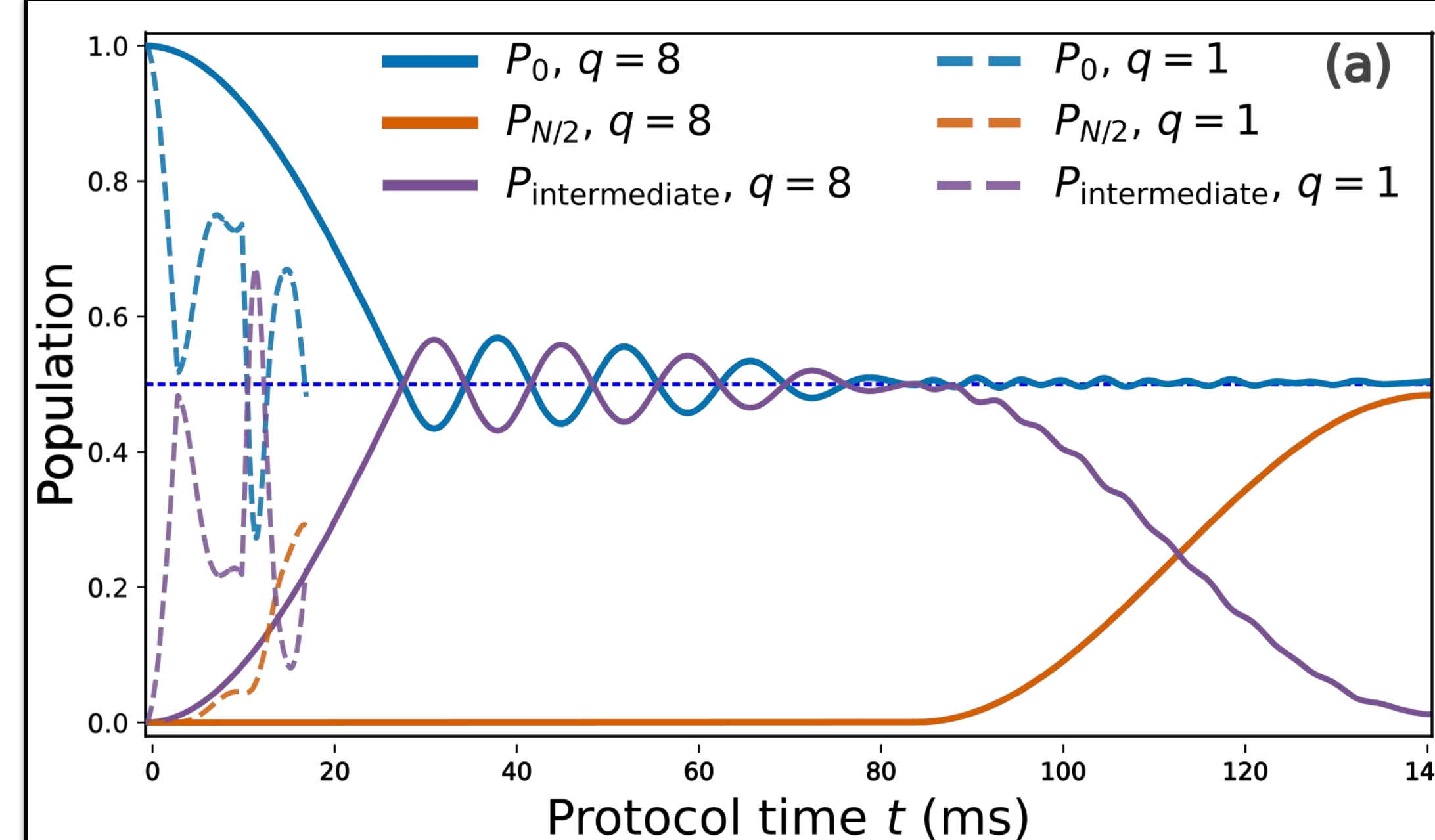
$$T_\pi^{(k)} = \frac{\pi}{\Omega_k} = \frac{\pi}{A_k d_k}, \quad T_{\pi/2}^{(k)} = \frac{\pi}{2\Omega_k} = \frac{\pi}{2A_k d_k}.$$

Probability to populate other states is given by

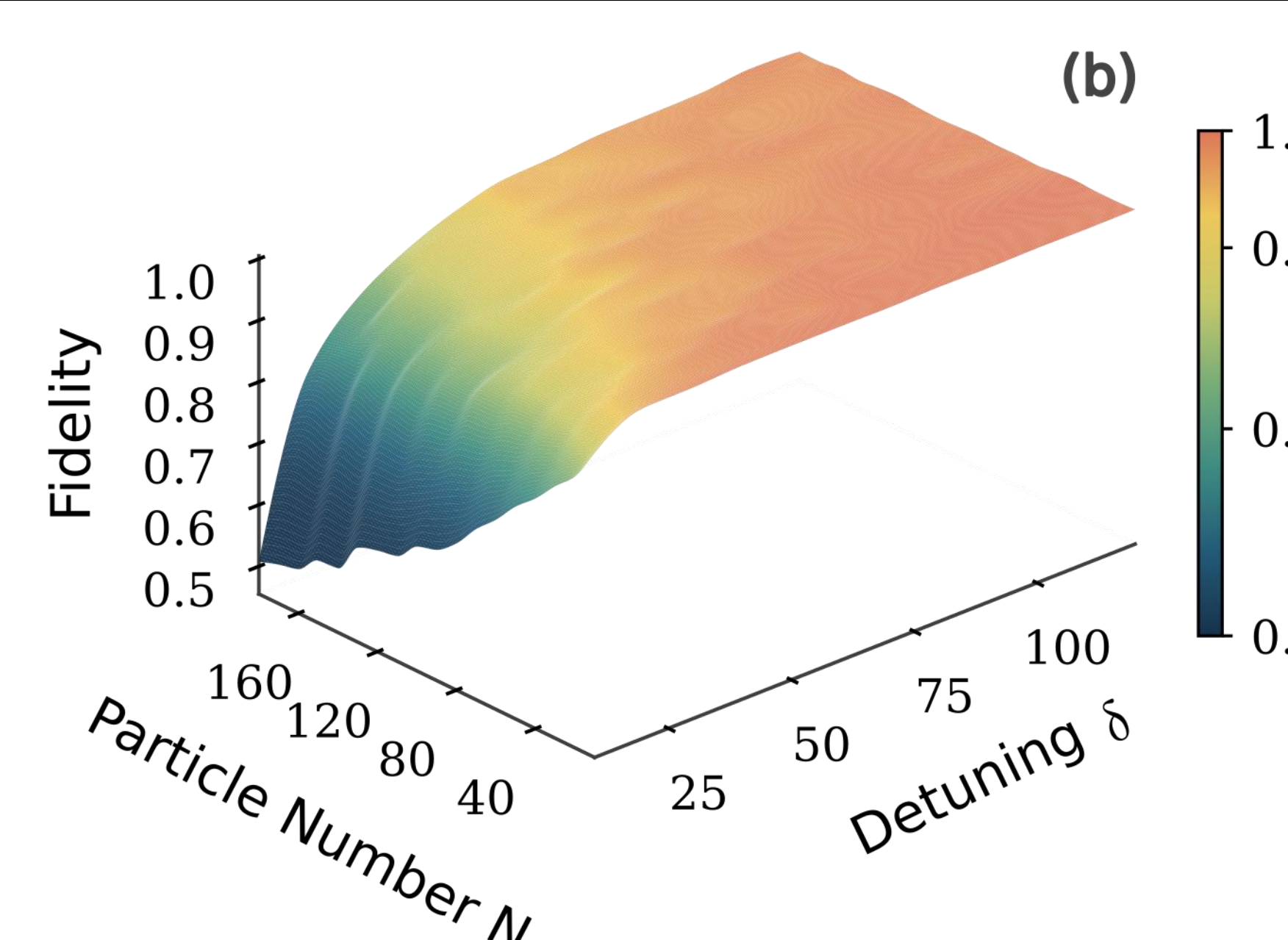
$$P_{\text{leak}}^{(k)} \approx \frac{\Omega_k^2}{\alpha_{\min}^2}, \quad \alpha_{\min} = \min_{l \neq k} |\omega_k - \omega_l|.$$



State transfer and Fidelity



(a) Dynamical population transfer in the course of the resonant pulse protocol for $N=6$. Selectivity parameter(q) is given by the ratio of transition anharmonicity to the Rabi frequency. (b) Attained Bell state fidelity for different atom number and molecular detunings.



Key Findings and Outlook

- ❖ Engineer a resonant-pulse protocol to prepare macroscopic atom-molecule Bell states.
- ❖ Achieve high fidelity of the produced maximally entangled Bell states with controllable relative phase.
- ❖ Optimization of the dynamical protocol characteristics to achieve reduced leakage.
- ❖ New pathways toward tailored many-body entangled configurations, including W states, for quantum information.
- ❖ Exploit atom-molecule Bell states as qubits.
- ❖ Explore the interplay of quantum and thermal fluctuations in the generation of atom-molecule entangled states.

References

- [1] G. A. Bougas, A. Vardi, H. R. Sadeghpour, C. Chin, and S. I. Mistakidis, Phys. Rev. Lett. **137**, 093401 (2026)
- [2] J. Calsamiglia, M. Mackie, and K.-A. Suominen, Phys. Rev. Lett. **87**, 160403 (2001)
- [3] Z. Zhang, S. Nagata, K.-X. Yao, and C. Chin, Nat. Phys. **19**, 1466-1470 (2023)
- [4] Z. Zhang, L. Chen, K.-X. Yao, and C. Chin, Nature **592**, 708-711 (2021)

Acknowledgement

We acknowledge the support of the Missouri S&T College of Engineering and Computing, Department of Physics, Missouri S&T and the University of Missouri Quantum Innovation Center.