Non-adiabatic generation of NOON states in a Tonks–Girardeau gas

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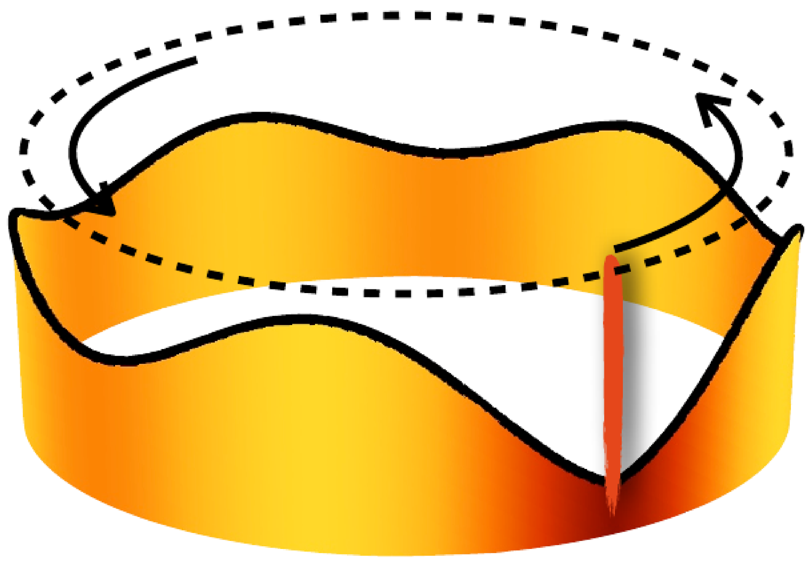
Introduction

- Quantum superposition states are difficult to generate experimentally. One example is the NOON state.
  - The $|N,0\rangle + |0,N\rangle$ or "NOON" state is a superposition state where all particles can be found in either one state or another.
  - This state requires strong correlations between particles.
- This project studies the following:
  - The generation of NOON states in a ring of strongly correlated, ultracold atoms through an adiabatic technique.
  - The application of the Chopped RAndom Basis (CRAB) Optimal Control [1] along with Shortcuts to Adiabaticity (STA) techniques to generate NOON states non-adiabatically.

Rotating Ring Trap

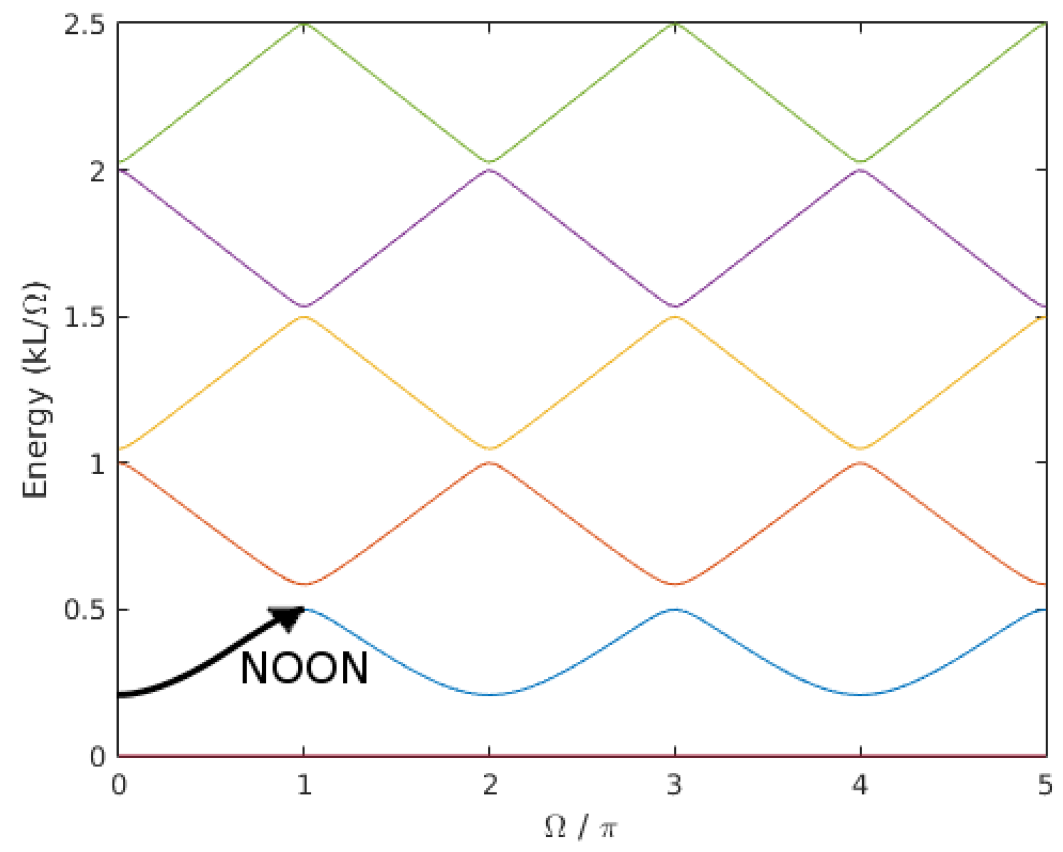
- Our system is a ring of strongly correlated ultracold atoms in the Tonks-Girardeau regime with the following properties:
  - The bosons are fermionized.
  - It is 1-dimensional with periodic boundaries.
  - There is potential barrier that "stirs" the trap.



- We can model a system of N atoms with a mass M in a loop with a circumference of L with the 1-dimensional Hamiltonian [2]

$$\sum_{i=0}^{N}\left[\frac{\hbar}{2M}\left(-i\frac{\partial}{\partial x_i}-\Omega\right)^2+b\delta(x_i)+g\sum_{i<j}^{N}\delta(x_i-x_j)\right],$$

- A single particle will rotate and form different rotational states, shown in the energy spectrum (below).
  - With a barrier present, there are avoided crossings in the rotational states at integer values of π.
  - NOON states are found at the positions of the avoided crossings



CRAB Algorithm

- The Chopped RAndom Basis (CRAB) Optimal Control technique changes a guess pulse [1]

$$\Omega_j^{CRAB}(t) = \Omega_j^0(t)g_j(t)$$

Ω_j^0 is an initial guess we provide that is modified by $g_j(t)$, the function to be optimized

$$g(t) = 1 + \frac{\sum_{n=0}^{N} A_n\sin(\omega_n t) + B_n\cos(\omega_n t)}{\lambda(t)}$$

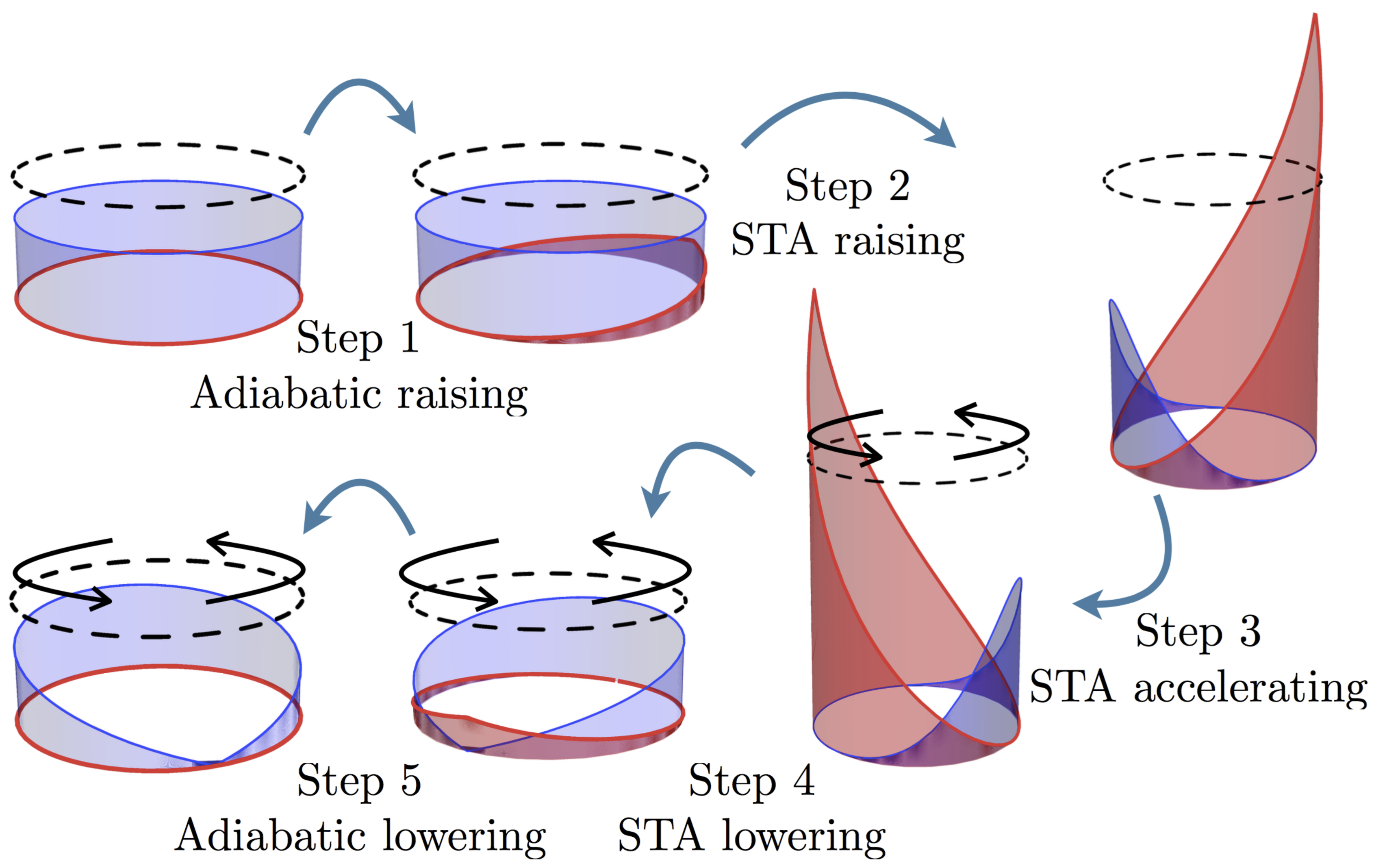
Where $\lambda(t)$ is a function, chosen such that $\lambda(t)\to\infty$ for $t\to 0$ and $t\to T$. In our implementation,

$$\lambda(t) = \frac{T^2}{4t(t-T)}$$

- This technique is performed continually with the Nelder–Mead, or "downhill simplex," method to maximize the fidelity (or closeness) to the NOON state.

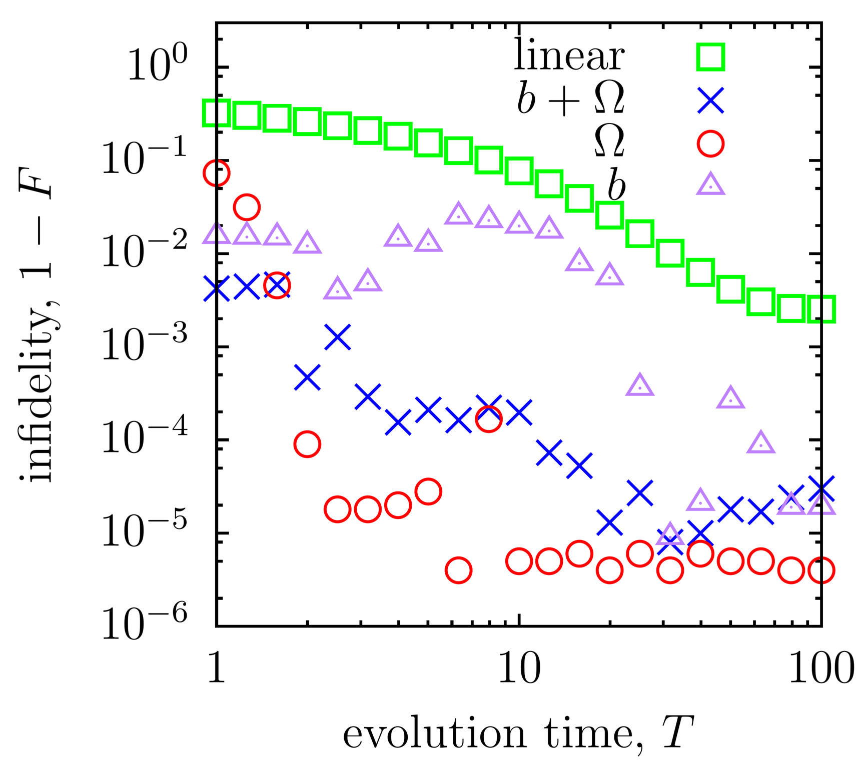
STA techniques

- STA techniques use semi-analytical shortcuts to speed up quantum adiabatic processes.
- Our technique initially raises a potential adiabatically and then rotates the system into the desired state.
- In contrast to optimal control, STA techniques have a lower numerical complexity, but have initially adiabatic steps.

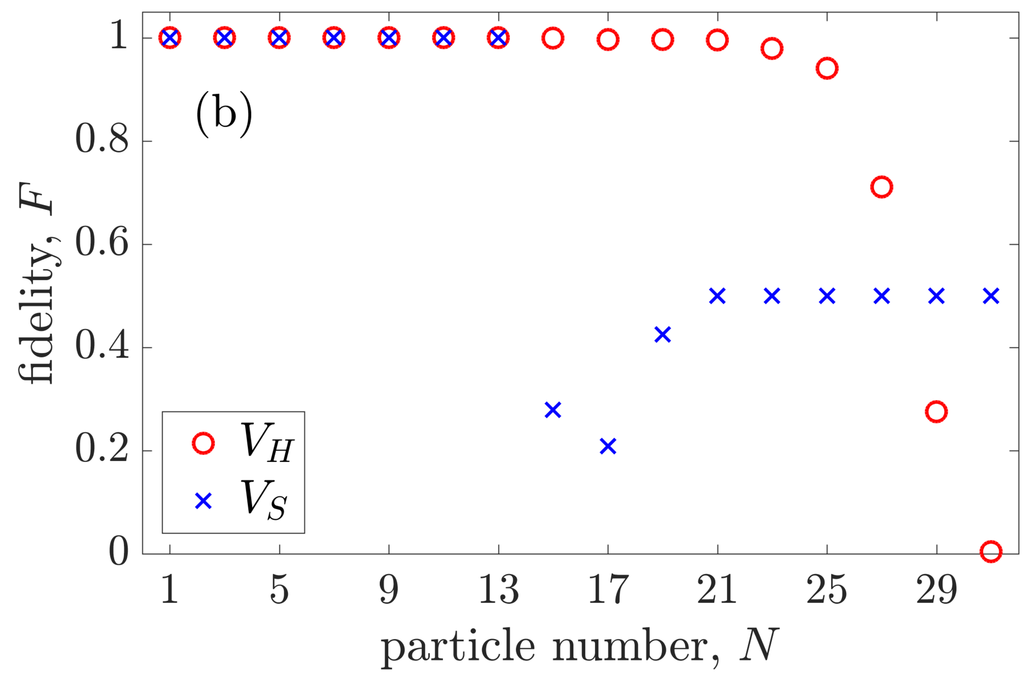


Results

- With the CRAB algorithm, we found optimal rotational pulses at much shorter timescales than with STA techniques.
- It is also possible to manipulate the barrier height with the CRAB algorithm.



- With STA tecniques, we found high fidelities until $N = 15$ bosons for a harmonic trap V_H and $N = 21$ for a sinusoidal trap V_S.



Conclusions

We have shown:

- It is possible to manipulate either the rotation or barrier heght within a specified time regime to create NOON states on a rotating ring of strongly correlated ultracold atoms by using the CRAB optimal control technique.
- We may generate NOON states with STA in this system with up to $N = 15$ bosons for a harmonic trap and $N = 21$ for a sinusoidal trap.

These results have been published in [3].

[1] T. Caneva, T. Calarco and S. Montangero, *Phys. Rev. A*, 84:022326 (2011)
[2] D. Hallwood, T. Ernst and J. Brand, *Phys. Rev. A*, 82:063623 (2010)
[3] J. Schloss, A. Benseny, J. Gillet, J. Swain and Th. Busch, *New J. of Phys.* 18:035012 (2016)