Spin chains using strongly interacting cold atoms

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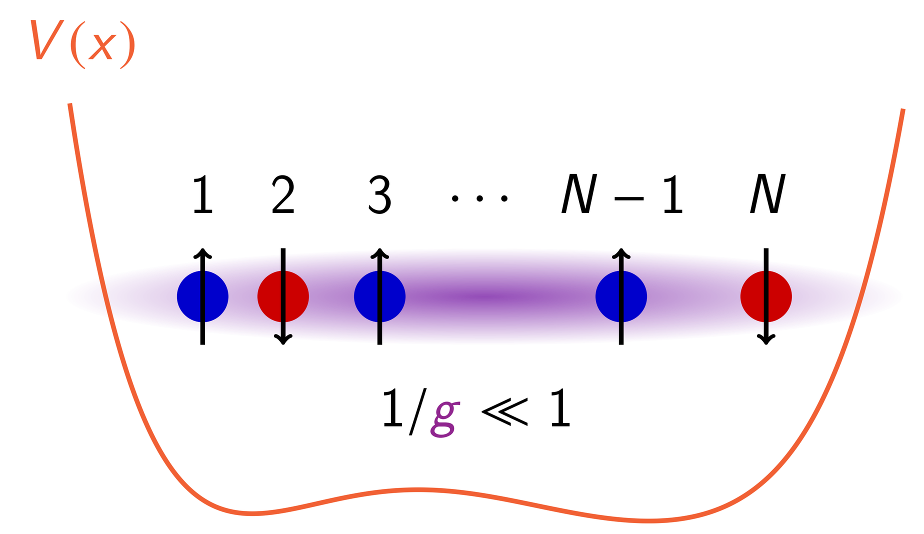
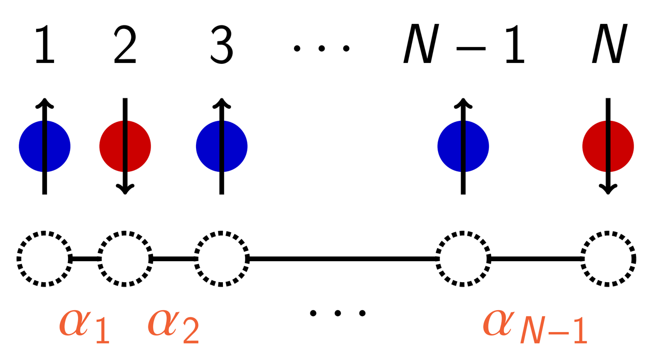
Strongly interacting cold atomic gas



$\longrightarrow$

Spin chain model



$$H = \sum_{i=1}^{N} -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_i^2} + V(x_i) + \sum_{\uparrow\downarrow\text{ pairs}} g\,\delta(x_i - x_j) + \sum_{\substack{\uparrow\uparrow\text{ pairs}\\ \downarrow\downarrow\text{ pairs}}} g\kappa\,\delta(x_i - x_j)$$

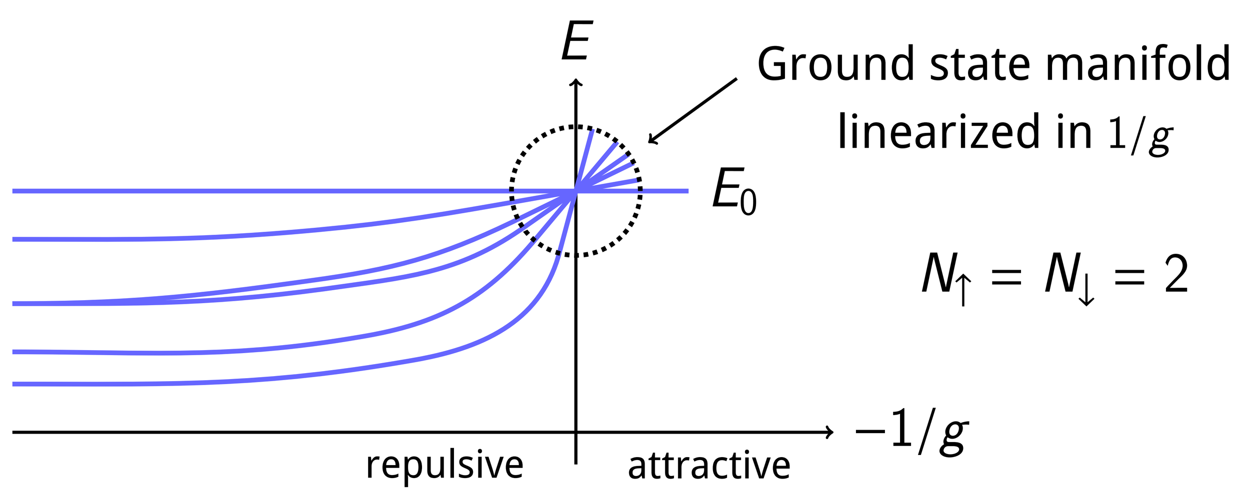
$$H_0 = E_0 - \sum_{k=1}^{N-1} \frac{\alpha_k}{g}\left[\frac{1}{2}\left(1 - \boldsymbol{\sigma}^k \cdot \boldsymbol{\sigma}^{k+1}\right) + \frac{1}{\kappa}\left(1 + \sigma_z^k \sigma_z^{k+1}\right)\right]$$

Abstract

By tuning the potential $V(x)$ trapping a strongly interacting cold atomic gas one can engineer the local exchange coefficients α_k in the effective spin chain model.

Background

- N cold atoms in a 1D trap potential $V(x)$.
- Degenerate ground state manifold with energy E_0 in strongly interacting limit, $g \to \infty$.
- Map the system onto a spin model to first order in $1/g$.
  $0 < \kappa < \infty$: bosons in XXZ model.
  $\kappa \to \infty$: bosons or fermions in XXX model.
  $\kappa = 2$: bosons in XX model.



Local exchange coefficients given by

$$\alpha_k = \int \cdots \int_{x_1 < \cdots < x_{N-1}} dx_1 \cdots dx_{N-1} \left(\frac{\partial \Phi_0(x_1, \ldots, x_N)}{\partial x_N}\right)^2_{x_N = x_k}$$

for $k = 1, \ldots, N-1$.

- Φ_0 is the Slater determinant of non-interacting states.
- α_k depends only on $V(x)$ and N.

Method

We developed the CONAN software that computes the local exchange coefficients.

CONAN

$V(x) \to$ [QR code] $\to \alpha_k$

arXiv:1603.02662

- Highly efficient code: $N = 10$ in circa 10 seconds and the computation time scales $O(N^{3.5\pm0.4})$.
- High precision up to $N = 30$ and acceptable up to $N = 35$.

Application: quantum state transfer

Transfer a spin through the chain: $|\uparrow\downarrow\cdots\downarrow\downarrow\rangle \longrightarrow |\downarrow\downarrow\cdots\downarrow\uparrow\rangle$.

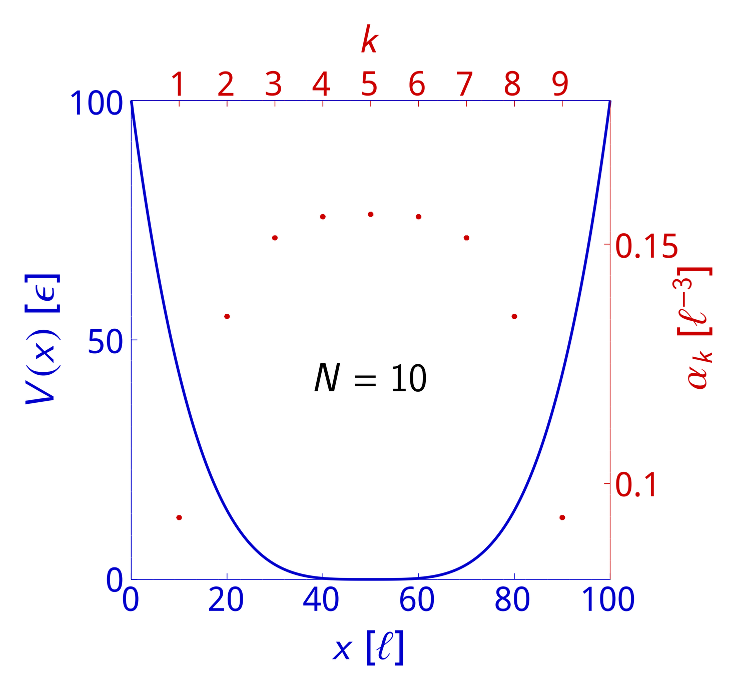
State transfer is perfect when the transfer fidelity is unity:

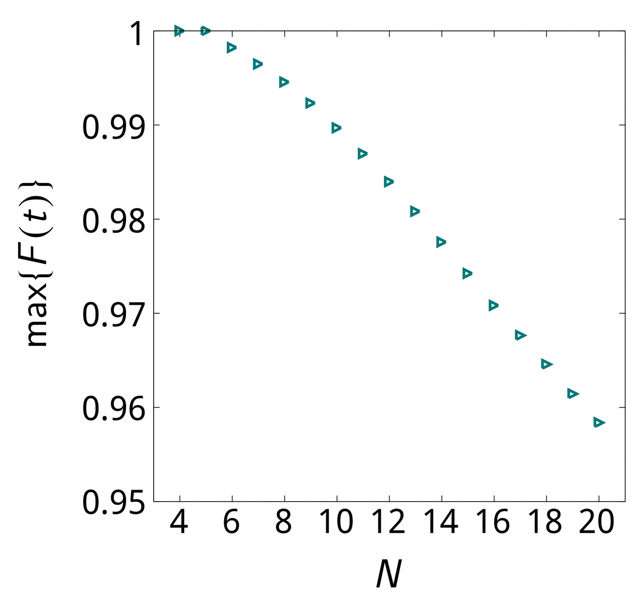
$$F(t) := \left|\langle\downarrow\downarrow\cdots\downarrow\uparrow|\, e^{-iH_0 t/\hbar}\, |\uparrow\downarrow\cdots\downarrow\downarrow\rangle\right|^2 = 1\,.$$

Perfect state transfer is known to occur in an XX model if

$$\alpha_k \propto \sqrt{k(N-k)}\,.$$

Use CONAN to search for a $V(x)$ that produces these local exchange coefficients. We reach perfect or nearly perfect state transfer.





We study how noise directly on $V(x)$ influences the state transfer in the spin model, i.e. *before* the lattice approximation.

The state transfer properties can tolerate moderate noise. We propose a cold-atom implementation of the system.

Perspectives

- Inverted problem: Use CONAN to find a potential that produces a spin model with given local exchange coefficients or energy spectrum.
- Higher energies: Generalize the procedure to excited state manifolds and include finite temperature effects.

References

N. J. S. Loft, L. B. Kristensen, A. E. Thomsen, A. G. Volosniev, and N. T. Zinner: CONAN – the cruncher of local exchange coefficients for strongly interacting confined systems in one dimension, *arXiv*:1603.02662 (2016)

N. J. S. Loft, O. V. Marchukov, D. Petrosyan, and N. T. Zinner: Tunable self-assembled spin chains of strongly interacting cold atoms for demonstration of reliable quantum state transfer, *New J. Phys.*, in press (2016)