Recovering quantum correlations in optical lattices from interaction quenches

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Quantum simulation experiments with ultra-cold atoms [1] have lead to numerous insights into the physics of strongly correlated quantum systems, e.g., realizing and observing anti-ferromagnets [2] with substantial evidence of string patterns [3]. It is fair to say that there has been steady progress towards realizing the ambitious long-term goals set for quantum simulators [4]. In the future developing diagnostic tools regarding genuine quantum correlations in such systems will become key. The atom gas microscope is the state-of-the-art diagnostic tool and enables a level of inquiry into ultra-cold atoms in optical lattices unparalleled in any other quantum many-body system opening an exciting pathway towards understanding strongly interacting quantum systems. However, currently a direct measurement of a coherent current is out of reach. In this work, we show how to unify the two principal read-out techniques in optical lattice quantum simulators by using atom microscope measurements together with time-of-flight expansion into an optical superlattice. For this, we establish a data analysis method not resorting to the far-field approximation which reliably recovers the full covariance matrix, including off-diagonal correlations representing coherent currents. The signal processing builds upon semi-definite optimization, providing bona fide covariance matrices optimally matching the observed data. We demonstrate how the obtained information about non-commuting observables allows to lower bound entanglement at finite temperature which opens up the possibility to study quantum correlations in quantum simulations going beyond the capabilities of classical computers.

We consider fermionic atoms in optical lattices and show how to use readily available quench protocols to perform tomographic reconstructions based on atom microscope measurements. Our protocol consists of four steps: (a) Prepare a fermionic state, (b) Double-up the lattice locally, (c) Quench to the nearest-neighbour hopping Hamiltonian in the new lattice, (d) Measure on-site particle numbers using the atom microscope. The results of the numerical reconstruction [5], involving semi-definite positivity constraints, of correlations in a thermal state are presented in Fig. 1. It is crucial that *i)* there is no need of new experimental developments, our novel reconstruction method is the innovation, *ii)* the measurements need not be perfect and Fig. 1 includes statistical noise, *iii)* in the submitted paper we show that the reconstruction allows to quantify entanglement present in the system using a novel entropic witness. These three points are fully in line with very encouraging feedback from experimentalists who have shown much interest in our new tomographic reconstruction method and applying it experimentally is now our main focus.

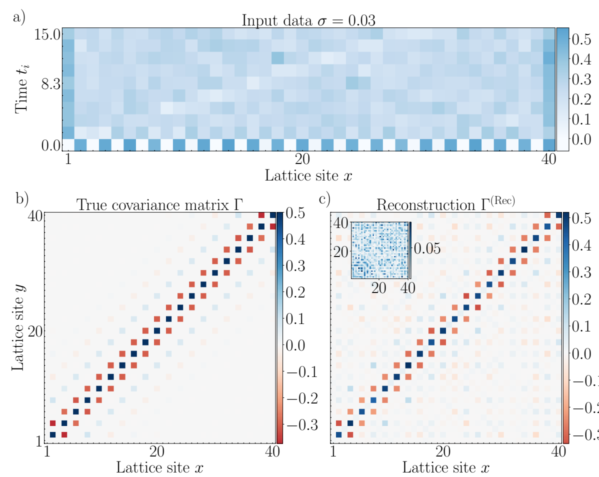

FIG. 1. **Tomographic reconstruction.** *a)* Input data for the reconstruction based on out-of-equilibrium data of local particle numbers $N_x(t_i)$ as would be measured by the atom microscope. *b)* The true input covariance matrix representing a thermal state. We have chosen a temperature so that there are relatively large currents to be recovered. The covariance matrix Γ is shown after step (b) after the sub-lattice has been created. Note that besides the new checker-board pattern, the correlations between sites are assumed to be exactly preserved. *c)* Results of the reconstruction $\Gamma^{(\mathrm{Rec})}$ which works even in presence of statistical noise.

[1] I. Bloch, J. Dalibard, and S. Nascimbene, Nature Phys. **8**, 267 (2012).
[2] A. Mazurenko, C. S. Chiu, G. Ji, M. F. Parsons, M. Kanasz-Nagy, R. Schmidt, F. G. E., Demler, , Greif, and M. Greiner, Nature **545**, 462 (2017).
[3] C. S. Chiu, G. Ji, A. Bohrdt, M. Xu, M. Knap, E. Demler, F. Grusdt, M. Greiner, and D. Greif, Science **365**, 251 (2019), https://science.sciencemag.org/content/365/6450/251.full.pdf.
[4] A. Acin, I. Bloch, H. Buhrman, T. Calarco, C. Eichler, J. Eisert, D. Esteve, N. Gisin, S. J. Glaser, F. Jelezko, S. Kuhr, M. Lewenstein, M. F. Riedel, P. O. Schmidt, R. Thew, A. Wallraff, I. Walmsley, and F. K. Wilhelm, New J. Phys. **20**, 080201 (2018).
[5] M. Gluza, The numerical code is freely available at `https://github.com/marekgluza/hopping_tomography` and includes interactive Python notebooks allowing to reproduce the figures.