Coherent backscattering in the Fock space of ultracold bosonic atoms

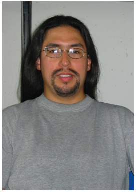
Peter Schlagheck

Université de Liège

16.2.2017

Coworkers

Thomas Engl
(Auckland)



Juan Diego Urbina
(Regensburg)

Klaus Richter
(Regensburg)

Julien Dujardin
(Luxembourg)

Arturo Argüelles
(Cali)

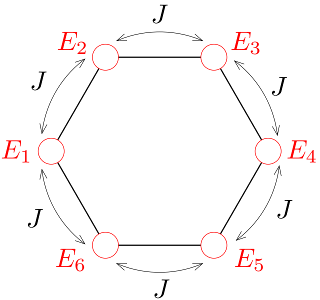
Outline

- Thermalization and localization in bosonic many-body systems
- Weak localization and coherent backscattering
- Coherent backscattering in Fock space
- Verification with ultracold atoms
- Conclusion

Interacting bosonic many-body systems

We consider a one-dimensional disordered Bose-Hubbard ring:

$$\hat{H} = \sum_{l=1}^{L} \left[E_l \hat{b}_l^\dagger \hat{b}_l - J \left(\hat{b}_l^\dagger \hat{b}_{l-1} + \hat{b}_{l-1}^\dagger \hat{b}_l \right) + \frac{U}{2} \hat{b}_l^\dagger \hat{b}_l^\dagger \hat{b}_l \hat{b}_l \right]$$



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Regime of eigenstate thermalization:

J.M. Deutsch, PRA 43, 2046 (1991); M. Srednicki, PRE 50, 888 (1994); L. D'Alessio *et al.*, Adv. Phys. 65, 239 (2016)

$\longrightarrow$ all many-body eigenstates are equidistributed within the classical phase space of the system

$\longrightarrow$ maximal entanglement entropy for subsystems

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$\longrightarrow$ Bose-Einstein distribution of the population of individual one-body eigenmodes

PS & D. Shepelyansky, PRE 93, 012126 (2016)

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I.V. Gornyi, A.D. Mirlin & D.G. Polyakov, PRL 95, 206603 (2005);
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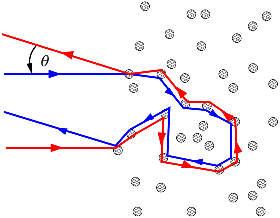
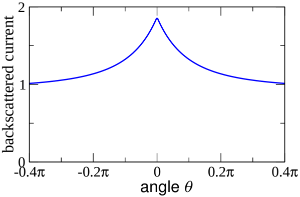
$\rightarrow$ weak localization in the Fock space of many-body systems?

Coherent backscattering in disordered systems

→ constructive wave interference between reflected classical paths and their time-reversed counterparts





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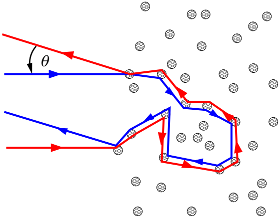

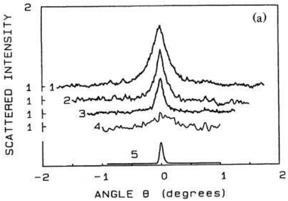

- coherent backscattering of laser light in disordered media

  M. P. Van Albada and A. Lagendijk, PRL 55, 2692 (1985)

  P.-E. Wolf and G. Maret, PRL 55, 2696 (1985)

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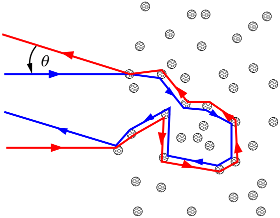

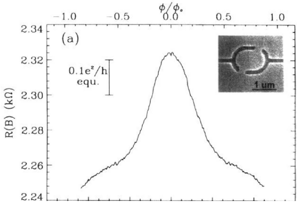

- coherent backscattering of laser light in disordered media
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  A. M. Chang *et al.*, PRL 73, 2111 (1994)

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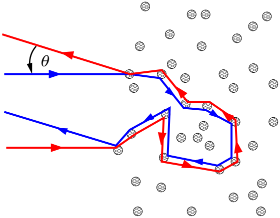
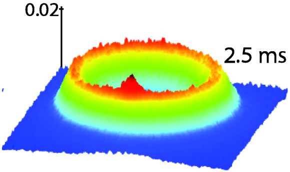
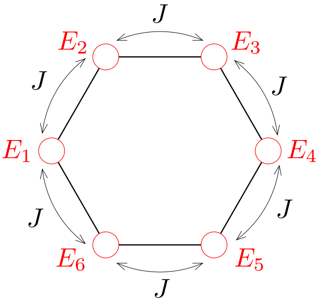




- coherent backscattering of laser light in disordered media
- magnetoresistance within two-dimensional electron gases
- coherent backscattering of ultracold atoms in 2D disorder
  F. Jendrzejewski *et al.*, PRL 109, 195302 (2012)
  (see also N. Cherroret *et al.*, PRA 85, 011604(R) (2012))

Many-body CBS in disordered Bose-Hubbard rings

$$\hat{H} = \sum_{l=1}^{L} \left[E_l \hat{b}_l^\dagger \hat{b}_l - J \left(\hat{b}_l^\dagger \hat{b}_{l-1} + \hat{b}_{l-1}^\dagger \hat{b}_l \right) + \frac{U}{2} \hat{b}_l^\dagger \hat{b}_l^\dagger \hat{b}_l \hat{b}_l \right]$$



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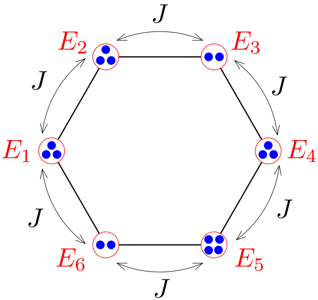

Start with a given initial Fock state, e.g. $|\mathbf{n}^{\mathrm{i}}\rangle = |3, 3, 2, 3, 4, 2\rangle$, and determine the probability to reach a given final Fock state $|\mathbf{n}^{\mathrm{f}}\rangle = |n_1^{\mathrm{f}}, \ldots, n_L^{\mathrm{f}}\rangle$ at time t under some disorder average

Semiclassical van Vleck-Gutzwiller approach

Represent the quantum transition amplitude

$$\langle \mathbf{n}^{\mathrm{f}} | \hat{U} | \mathbf{n}^{\mathrm{i}} \rangle \equiv \langle \mathbf{n}^{\mathrm{f}} | \exp[-\tfrac{i}{\hbar} t \hat{H}] | \mathbf{n}^{\mathrm{i}} \rangle = \sum_\gamma A_\gamma e^{i R_\gamma / \hbar}$$

in terms of classical (Gross-Pitaevskii) trajectories γ satisfying

$$i\hbar \frac{\partial}{\partial t} \psi_l(t) = E_l \psi_l(t) - J \left[\psi_{l+1}(t) + \psi_{l-1}(t) \right] + U \left(|\psi_l(t)|^2 - 1 \right) \psi_l(t)$$

with $\psi_l(0) = \sqrt{n_l^{\mathrm{i}} + 0.5}\, e^{i\theta_l^{\mathrm{i}}}$ and $\psi_l(t) = \sqrt{n_l^{\mathrm{f}} + 0.5}\, e^{i\theta_l^{\mathrm{f}}}$
for all $l = 1, \ldots, L$ with some arbitrary phases $0 \leq \theta_l^{\mathrm{i/f}} < 2\pi$

$R_\gamma =$ classical action of the trajectory γ

$A_\gamma =$ stability amplitude (related to Lyapunov exponent) of γ

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Average detection probability of the Fock state $|\mathbf{n}^{\mathrm{f}}\rangle$:

$$\overline{|\langle \mathbf{n}^{\mathrm{f}} | \hat{U} | \mathbf{n}^{\mathrm{i}} \rangle|^2} = \textstyle\sum_{\gamma,\gamma'} \underbrace{\overline{A_\gamma A_{\gamma'} e^{i(R_\gamma - R_{\gamma'})/\hbar}}}_{= 0 \text{ if } R_\gamma \neq R_{\gamma'}}$$

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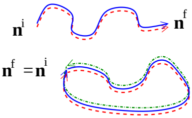
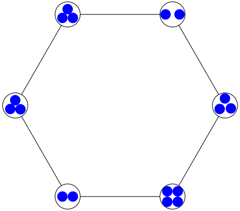
$\overline{|\langle \mathbf{n}^{\mathrm{f}} | \hat{U} | \mathbf{n}^{\mathrm{i}} \rangle|^2} = \sum_\gamma |A_\gamma|^2$ if $\mathbf{n}^{\mathrm{f}} \neq \mathbf{n}^{\mathrm{i}}$

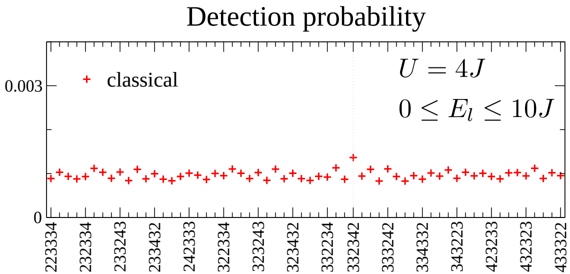
$\overline{|\langle \mathbf{n}^{\mathrm{i}} | \hat{U} | \mathbf{n}^{\mathrm{i}} \rangle|^2} = 2 \sum_\gamma |A_\gamma|^2$ due to CBS



Comparison with numerical data

Initial state:





$$\overline{\langle \mathbf{n}^{\mathrm{f}} | \hat{U} | \mathbf{n}^{\mathrm{i}} \rangle |^2}^{\,\text{classical}} = \sum_\gamma |A_\gamma|^2$$

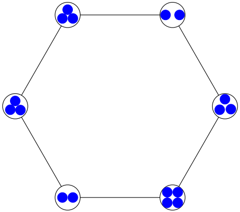
$$= \int_0^{2\pi} \frac{d\theta_2^{\mathrm{i}}}{2\pi} \cdots \int_0^{2\pi} \frac{d\theta_L^{\mathrm{i}}}{2\pi} \prod_{l=2}^{L} \delta\left(n_l^{\mathrm{f}} + 0.5 - |\psi_l(t; n_1^{\mathrm{i}}, 0, n_2^{\mathrm{i}}, \theta_2^{\mathrm{i}} \ldots n_L^{\mathrm{i}}, \theta_L^{\mathrm{i}})|^2 \right)$$

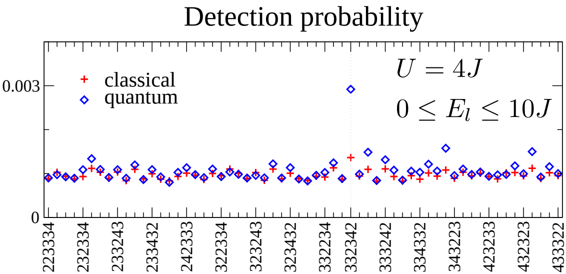
in the presence of classical chaos and ergodicity

J.H. Hannay & A.M. Ozorio de Almeida, JPA 17, 3429 (1984)

Comparison with numerical data

Initial state:





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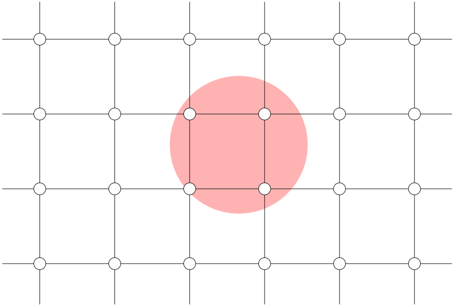
$\longrightarrow$ significant deviation from quantum ergodicity

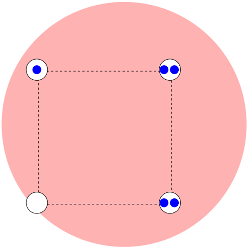
$\longrightarrow$ observable in a cold-atom experiment?

Proposal for a few-body CBS experiment



Consider an isolated 2D sheet of a 3D optical lattice within which you isolate a single plaquette (e.g. by means of a focused red-detuned laser beam)

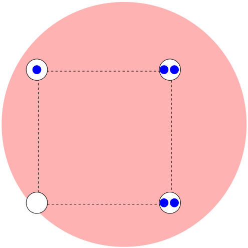
Proposal for a few-body CBS experiment



Experimental procedure:

1. Load the plaquette with a well-defined number of bosonic atoms in the deep Mott-insulator regime

Proposal for a few-body CBS experiment



2. Add some disorder (by means of an optical speckle field) and/or randomly displace the focus of the red-detuned laser beam

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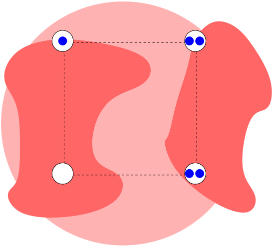

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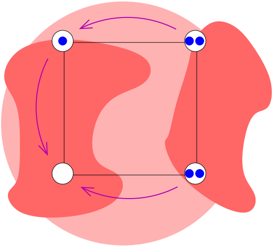
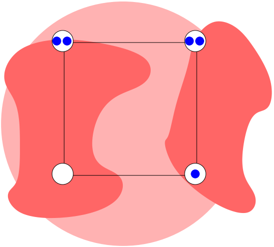


3. Switch on the inter-site hopping and let the atoms move . . .

Proposal for a few-body CBS experiment



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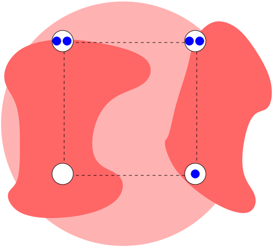
Proposal for a few-body CBS experiment



4. Quench back to the Mott regime after a given evolution time and detect the atomic population on each site

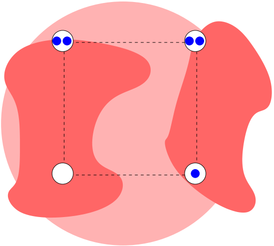
W. Bakr *et al.*, Nature 462, 74 (2009)

J. Sherson *et al.*, Nature 467, 68 (2010)

A.M. Kaufman *et al.*, Science 353, 794 (2016)
($\rightarrow$ beyond binary populations)

Proposal for a few-body CBS experiment

2 2 1 0



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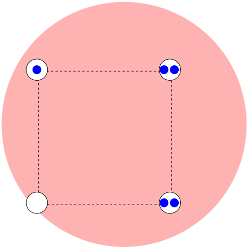
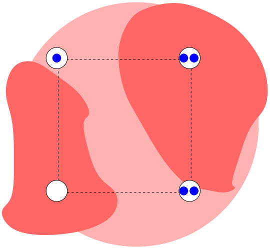


2 2 1 0

5. Repeat the experiment with the same initial state but for a different disorder configuration

Proposal for a few-body CBS experiment



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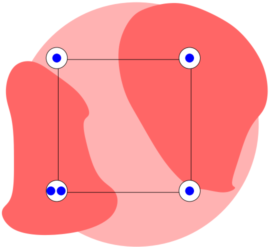

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1 1 1 2
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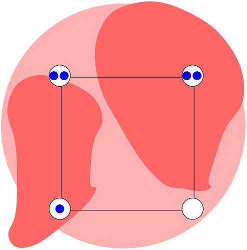

2	2	1	0
1	1	1	2
2	2	0	1

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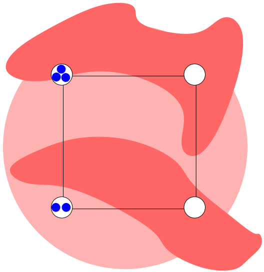
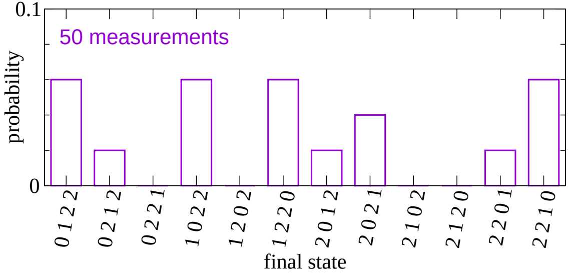


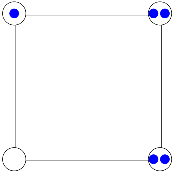
2	2	1	0
1	1	1	2
2	2	0	1
3	0	0	2

5. Repeat the experiment with the same initial state but for a different disorder configuration

Proposal for a few-body CBS experiment

Numerical simulation of the experiment for the parameters $U = J$, $0 < E_l < 4J$ and the evolution time $t = 10\hbar/J$





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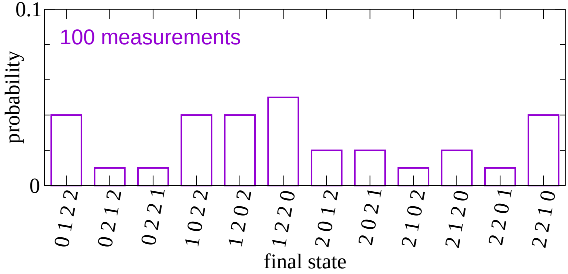

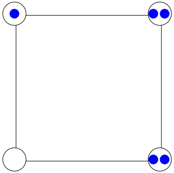

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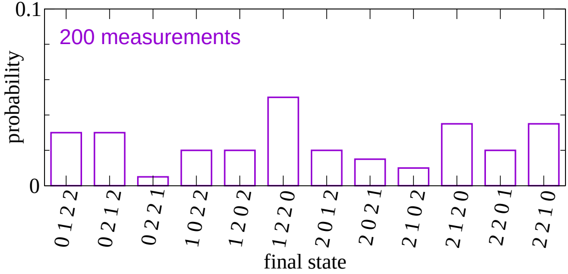

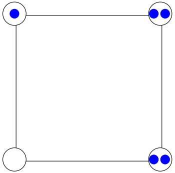

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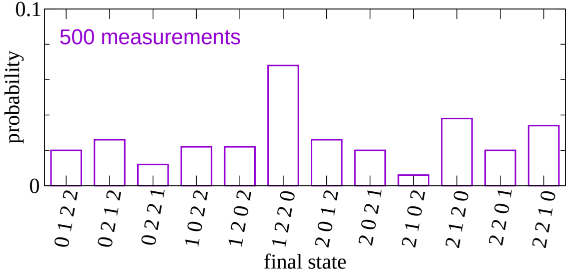

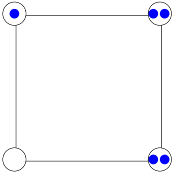

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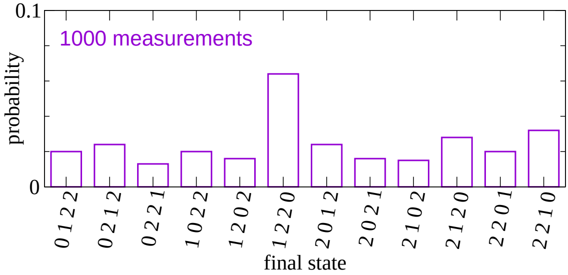

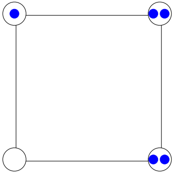

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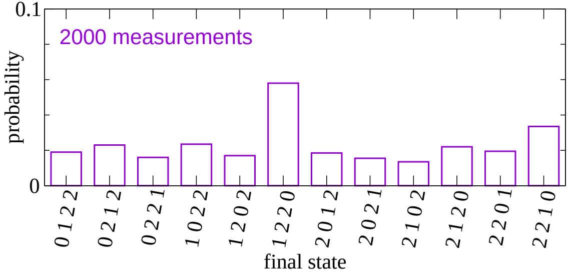

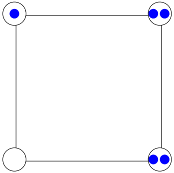

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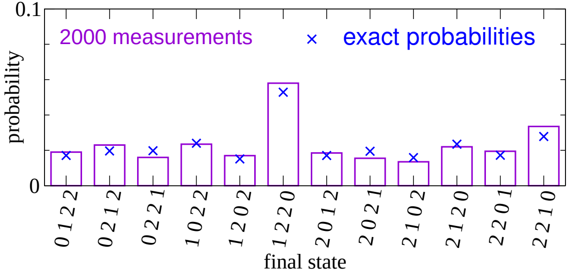

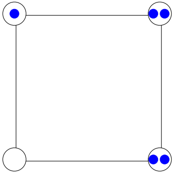

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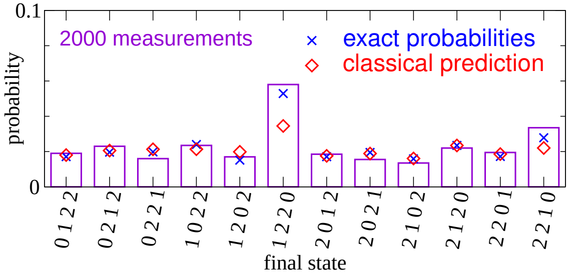

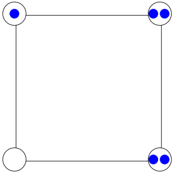

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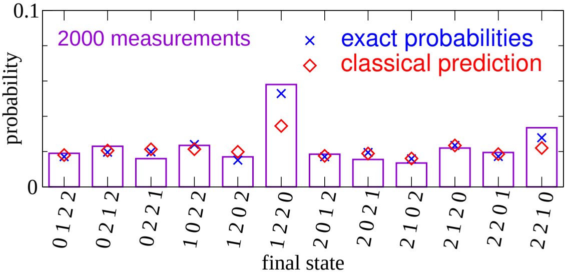

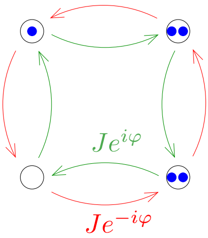

$\longrightarrow$ induce a synthetic gauge field in order to break time-reversal invariance

Y.J. Lin *et al.*, Nature 462, 628 (2009)

N. Goldman *et al.*, PRL 105, 255302 (2010)

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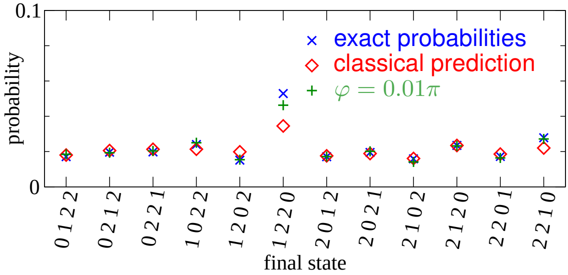

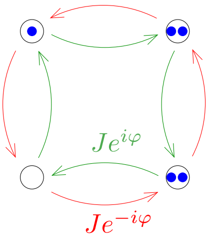

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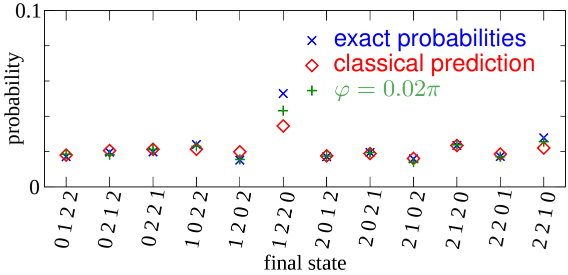

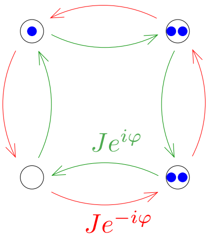

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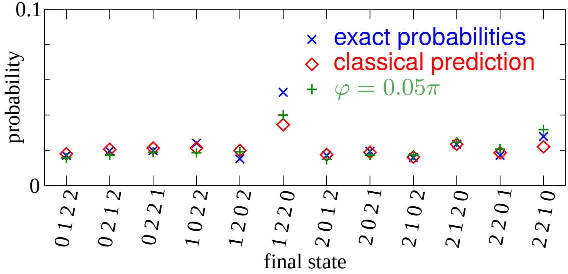

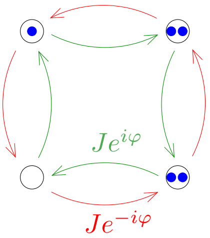

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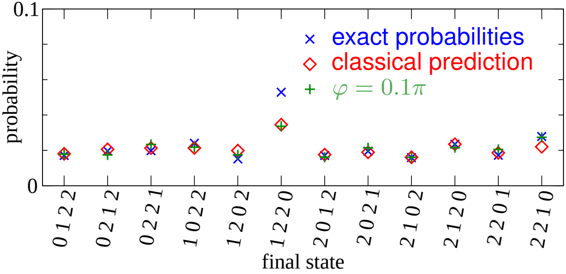

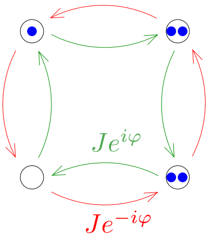

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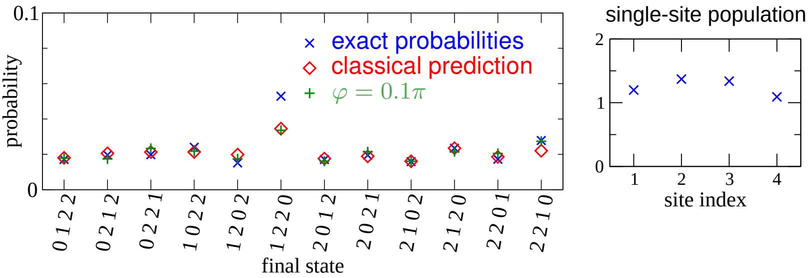

$\longrightarrow$ slightly inhomogeneous single-site populations

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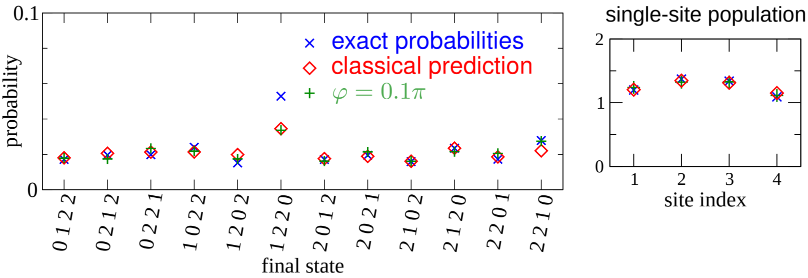
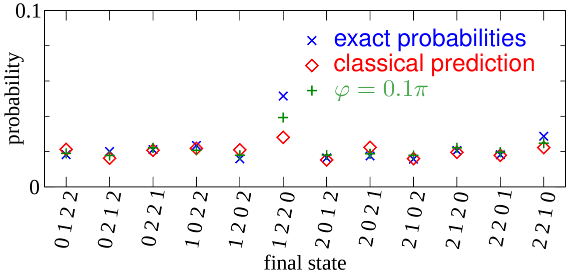
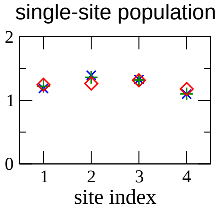


$\longrightarrow$ slightly inhomogeneous single-site populations due to limited classical ergodicity at $t = 10J/\hbar$

Proposal for a few-body CBS experiment

Numerical simulation of the experiment for the parameters $U = J$, $0 < E_l < 4J$ and the evolution time $t = 100\hbar/J$





$\longrightarrow$ slightly inhomogeneous single-site populations
due to limited classical ergodicity at $t = 10J/\hbar$ and
due to quantum (few-body) localization at $t = 100\hbar/J > \tau_H$

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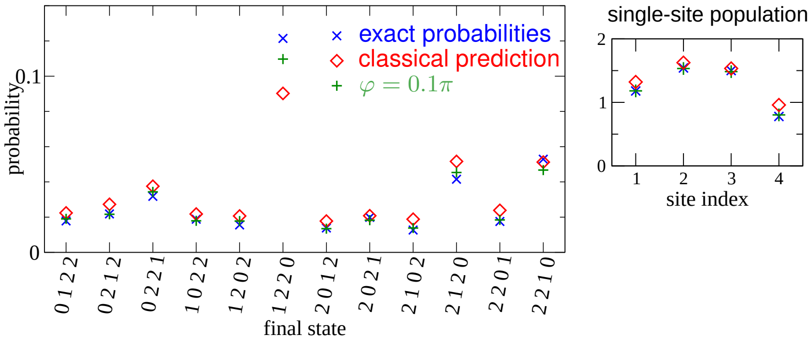

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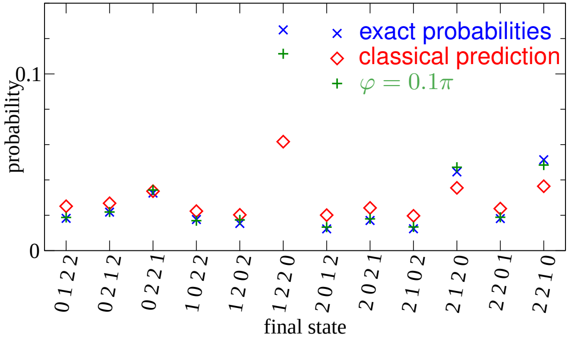

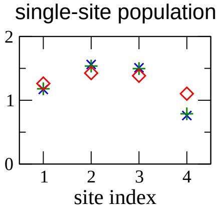

Conclusion

Coherent backscattering in Fock space

- privileges, on average, the initial Fock state as compared to other states with comparable energy;
- significantly affects quantum ergodicity in finite systems, in a regime where the classical dynamics is fully ergodic;
- can be experimentally detected using ultracold atoms in optical lattices;
- relies on time-reversal invariance and can therefore be switched off with a synthetic gauge field;
- can be generalized to fermions T. Engl *et al.*, arXiv:1409.5684 ;

$\rightarrow$ may act as a precursor to “strong” many-body localization?
D. Vollhardt & P. Wölfle, PRL 48, 699 (1982)