QUANTUM SIMULATION OF LATTICE GAUGE THEORIES WITH RYDBERG ATOMS

Federica Surace

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WHY GAUGE THEORIES AND QUANTUM SIMULATIONS?

High degree of control and tunability of quantum systems

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High degree of control and tunability of quantum systems

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- Use of **quantum simulators** for **strongly correlated** matter
- **Time evolution** of many-particle quantum systems

High degree of **control** and **tunability** of quantum systems
WHY GAUGE THEORIES AND QUANTUM SIMULATIONS?

- Access to real-time dynamics: perspectives for high energy physics
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- Access to **real-time** dynamics: perspectives for **high energy** physics
- Hope (long-term): overcome limitations of **experiments**, **classical computation**?

picture from T. Pichler, et al, Phys. Rev. X 6, 011023

picture from ELI, M. Marklund
WHY GAUGE THEORIES AND QUANTUM SIMULATIONS?

- Access to real-time dynamics: perspectives for high energy physics
- Hope (long-term): overcome limitations of experiments, classical computation?

→ LATTICE GAUGE THEORIES

Wiese, Annalen der Physik, 2013
Preskill, arXiv:1811.10085
Particles hopping around a plaquette acquire a phase
Static gauge fields

Particles hopping around a plaquette acquire a phase

Dynamical gauge fields

- additional degrees of freedom on links
Dynamical gauge fields

- additional degrees of freedom on links

\[ \psi_x^i \quad U_{x,x+1}^{ij} \quad x - 1 \quad x \quad x + 1 \]

condensed matter
frustrated magnets
quantum computing
toric code
high energy physics
standard model
Dynamical gauge fields

- additional degrees of freedom on links

\[ \psi^i_x \ U_{x,x+1}^{ij} \]

- Problem:
  - complex many-body interactions
  - local (gauge) symmetries

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We show that this has been done:

**U(1) GAUGE THEORY in 1+1d**

exploiting dynamics induced by *Rydberg* interactions
OUTLINE

The model

- Rydberg: FSS model
- U(1) gauge: quantum link model
OUTLINE

1. The model
   - Rydberg: FSS model
   - U(1) gauge: quantum link model

2. Slow dynamics
   - Density oscillations
   - String inversion
\[ \hat{H}_{\text{Ryd}} = \sum_{j=1}^{L} (\Omega \hat{\sigma}_j^x + \delta \hat{n}_j) + \sum_{j \neq \ell=1}^{L} V_{j,\ell} \hat{n}_j \hat{n}_\ell \]
RYDBERG ATOM EXPERIMENT


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\hat{H}_{\text{Ryd}} = \sum_{j=1}^{L} (\Omega \hat{\sigma}_j^x + \delta \hat{n}_j) + \sum_{j \neq \ell=1}^{L} V_{j,\ell} \hat{n}_j \hat{n}_\ell
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\[\hat{n}_j \hat{n}_{j+1} = 0\]
RYDBERG ATOM EXPERIMENT


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\]

\[\hat{n}_j \hat{n}_{j+1} = 0\]

Phase diagram, non-equilibrium dynamics (scars), ...
Fendley *PRB* 2004, Turner *Nat Phys* 2018, Lin *PRL* 2019, ...

Here: gauge theory
U(1) LATTICE GAUGE THEORIES

Matter (sites)

Fermions \{ \hat{\Phi}_i^\dagger, \hat{\Phi}_j \} = \delta_{i,j}
U(1) LATTICE GAUGE THEORIES

Matter (sites)

Fermions \( \{ \hat{\Phi}_i^+, \hat{\Phi}_j \} = \delta_{i,j} \)

Even sites: \( e^+ \)
Odd sites: \( e^- \)
U(1) LATTICE GAUGE THEORIES

Matter (sites)

Fermions

\{ \hat{\Phi}^\dagger_i, \hat{\Phi}_j \} = \delta_{i,j}

Even sites

\[ e^+ \]

Odd sites

\[ 0 \]

Gauge fields (links)

\[ [\hat{E}_{j,j+1}, \hat{U}_{j,j+1}] = \hat{U}_{j,j+1} \]
U(1) LATTICE GAUGE THEORIES

Matter (sites)

<table>
<thead>
<tr>
<th>Even sites</th>
<th>Odd sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>0</td>
</tr>
<tr>
<td>$e^-$</td>
<td></td>
</tr>
</tbody>
</table>

\[
\{ \hat{\Phi}_i^\dagger, \hat{\Phi}_j \} = \delta_{i,j}
\]

Gauge fields (links)

\[
[\hat{E}_{j,j+1}, \hat{U}_{j,j+1}] = \hat{U}_{j,j+1}
\]

\[
\hat{E} \rightarrow \hat{S}^z
\]

\[
\hat{E} |\uparrow\rangle = +\frac{1}{2} |\uparrow\rangle
\]

\[
\hat{U} \rightarrow \hat{S}^+
\]

\[
\hat{E} |\downarrow\rangle = -\frac{1}{2} |\downarrow\rangle
\]
**U(1) Lattice Gauge Theories**

**Matter (sites)**

- **Fermions**
  - Even sites: $e^+$
  - Odd sites: $e^-$

**Gauge fields (links)**

- $[\hat{E}_{j,j+1}, \hat{U}_{j,j+1}] = \hat{U}_{j,j+1}$
- $\hat{E} \rightarrow \hat{S}^z$
- $\hat{U} \rightarrow \hat{S}^+$

**Local symmetry**

$$\hat{G}_j = \hat{E}_{j,j+1} - \hat{E}_{j-1,j} - \left(\hat{\Phi}_j^\dagger \hat{\Phi}_j - \frac{1-(-1)^y}{2}\right)$$
U(1) LATTICE GAUGE THEORIES

Matter (sites)

Fermions

\[ \{ \hat{\Phi}^\dagger_i, \hat{\Phi}_j \} = \delta_{i,j} \]

Even sites: \( e^+ \)
Odd sites: \( 0 \)

Gauge fields (links)

\[ [\hat{E}_{j,j+1}, \hat{U}_{j,j+1}] = \hat{U}_{j,j+1} \]

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**U(1) Lattice Gauge Theories**

### Matter (sites)
- **Fermions**
  - Even sites: $e^+$
  - Odd sites: $e^-$
- \( \{ \hat{\Phi}_i^\dagger, \hat{\Phi}_j \} = \delta_{i,j} \)

### Gauge fields (links)
- Electric flux:
  - \( \hat{E}_{j,j+1} \)
  - Gauss law:
    - \( \hat{E} \ket{\uparrow} = +\frac{1}{2} \ket{\uparrow} \)
    - \( \hat{E} \ket{\downarrow} = -\frac{1}{2} \ket{\downarrow} \)
- Charge:
  - \( \hat{E}_{j,j+1} = \hat{U}_{j,j+1} \)

### Local symmetry
- \( \hat{G}_j = \hat{E}_{j,j+1} - \hat{E}_{j-1,j} - \left( \hat{\Phi}_j^\dagger \hat{\Phi}_j - \frac{1 - (-1)^j}{2} \right) \)
  - \( \hat{G}_j \ket{\Psi} = 0 \)
  - Gauss law:
    - \( \hat{G}_j \ket{\Psi} = 0 \)
U(1) LATTICE GAUGE THEORIES

Matter (sites)

Fermions

\[ \{ \hat{\Phi}_i^\dagger, \hat{\Phi}_j \} = \delta_{i,j} \]

\begin{array}{c|c}
\text{Even sites} & e^+ \\
\hline
\text{Odd sites} & 0 \\
\end{array}

Gauge fields (links)

\[ [\hat{E}_{j,j+1}, \hat{U}_{j,j+1}] = \hat{U}_{j,j+1} \]

\[ \hat{E} \to \hat{S}^z \]

\[ \hat{E}\ket{\uparrow} = +\frac{1}{2}\ket{\uparrow} \]

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Local symmetry

\[ \hat{G}_j = \hat{E}_{j,j+1} - \hat{E}_{j-1,j} - \left( \hat{\Phi}_j^\dagger \hat{\Phi}_j - \frac{1 - (-1)^j}{2} \right) \]

\[ \hat{G}_j\ket{\Psi} = 0 \]

\[ [\hat{H}, \hat{G}_j] = 0 \]
U(1) lattice gauge theory constrained by Gauss Law

e^− e^+   ✓

\[ e^+  e^- \]

✗
Rydberg atoms constrained by Rydberg blockade

U(1) lattice gauge theory constrained by Gauss Law
Rydberg atoms constrained by Rydberg blockade

\[ \square \]

\[ \checkmark \] ✓ ✓ ✗ ✗

\[ 9/12 \]

U(1) lattice gauge theory constrained by Gauss Law

\[ \square \]

\[ \checkmark \] ✓ ✓ ✗ ✗

\[ 9/12 \]
There is an **exact mapping** of states and Hamiltonians
EXPERIMENT: SLOW DYNAMICS

EXPERIMENT: SLOW DYNAMICS

1) String
2) Pairs
3) Antistring
SUMMARY AND CONCLUSIONS

- U(1) lattice gauge theory is naturally realized in Rydberg atom arrays
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- Gauge theory interpretation of the dynamics
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Scattering of mesons in preparation
SUMMARY AND CONCLUSIONS

- U(1) lattice gauge theory is naturally realized in *Rydberg atom* arrays
- Gauge theory interpretation of the **dynamics**
- Dynamics of particle-antiparticle pairs, confinement are **experimentally accessible**

**Perspective:** Non-Abelian? Higher dimensionality?
THANK YOU FOR THE ATTENTION!

Paolo P. Mazza
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Alessio Lerose
Andrea Gambassi
Marcello Dalmonte