Quantum Simulation of Dynamical Gauge Fields: Experimental Approach

Apoorva Hegde, Alexander Mil, Torsten Zache, Andy Xia, Markus K. Oberthaler, Philipp Hauke, Jürgen Berges, Fred Jendrzejewski

Kirchhoff-Institut für Physik, Universität Heidelberg, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany
apoorna.hegde@kip.uni-heidelberg.de

Dynamical gauge fields

- Gauge theories are fundamental to Standard Model of High-Energy Physics (HEP). They are built up of fermionic and bosonic particles, which represent matter field and force carriers respectively.
- Requirements to simulate a HEP process using atomic systems:
  1. Work with finite dimensional Hilbert space, i.e. local implementation of gauge fields.
  2. Inclusion of both fermions and bosons.
  3. Interactions preserving local gauge invariance, i.e. satisfy Gauss' law.

- Realize the dynamical gauge field using ultracold atoms in optical lattices.
- Fermionic (mass) species reside on the lattice sites, bosonic (gauge field) on the links.

Schwinger pair production

- Vacuum becomes unstable at very high static electric fields leading to electron-positron pair creation.
- Pair production rate $P = \exp \left(-\frac{q^2}{2E_c}\right)$
- Critical field strength, $E_c = \frac{m_e q^2}{\hbar} = 10^{13} \text{Vm}^{-1}$
- $l_e = 10^{11} \text{Wm}^{-2}$

Can we construct a quantum simulator?

QED in 1+1D

- Quantum link model:
  - Gauge fields are replaced by quantum mechanical spins $\mathbf{I}_m$.
  - A discrete ‘Electric field’ is represented by $\mathbf{I}_m$.
- Formulation of U(1) gauge theories for cold atoms:
  - A. Kogut -Susskind formulation: A staggered lattice
    Kasper et al., NJP 19, 023030 (2017)
  - B. Wilson formulation: A tilted lattice
- Experimental implementation with atomic mixtures:

Gauge field

Matter field

Sodium

Lithium

\[ U(1) \text{ gauge theory in } 1+1D = \sum R \left[ \mathcal{H}_R + \hbar \left( \mathbf{I}_R \cdot \mathbf{p}_R + \frac{1}{2} \left( \mathbf{I}_R \cdot \mathbf{I}_R - \frac{1}{3} \mathbf{I}_R \cdot \mathbf{I}_R \right) \right] \]

\[ H_R = \sum_{R} \mathbf{L}_R \cdot \mathbf{p}_R + \frac{\Delta}{2} (\mathbf{I}_R \cdot \mathbf{I}_R) \]

Gauge field

Matter field

Gauge coupling

Building block

U-J. Wiese, 10.1002/andp.201300104


Initial state preparation

- Condensing $^{23}\text{Na}$ and $^7\text{Li}$ to quantum degeneracy:

\( \Lambda = 2.1156 \)

- Preparing coherent superposition of internal states in $^{23}\text{Na}$:

- Dynamics of particle production:

  - Spin changing collisions (SCC): Up to 6% of the total number of Li atoms are transferred from the "vacuum" state to the "particle" state after the quench.
  - The theoretical mean-field prediction of the Hamiltomian(red curve) is obtained by the model parameters $\chi, \Delta, \Lambda$.

- Tuning the gauge field: Resonant particle production

  - Keeping the interaction time fixed, the entire range of initial $L_z$ is scanned.
  - Resonance condition for observing SCC:
    \[ 2\chi L_z \approx \Delta \]
  - Changing the external magnetic field changes $\Delta$
    \[ \Delta(\mathbf{L}_z, B) = \Delta_{0} + \Delta_{1} \mathbf{L}_z + \Delta_{2} (B - B_{A})/B_{A} \]
  - Total magnetization is conserved.
  - Particle production is not observed for fields smaller than $B \sim 1.96 \text{ G}$ as the matter and the gauge field become too far off-resonant.

Outlook

- Lattice confinement with a 532 nm laser, with the lattice depth being much deeper for Na than Li.
- Connecting the building blocks with laser-assisted tunneling.
- Observe spin changing collisions between sodium and fermionic lithium.