Quantum Simulation of Dynamical Gauge Fields: Experimental Approach

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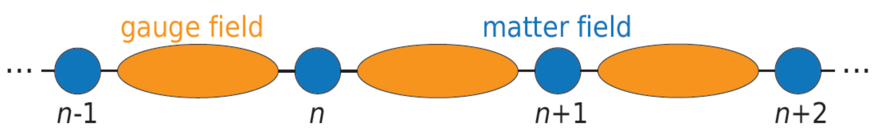
SynQS

Dynamical gauge fields

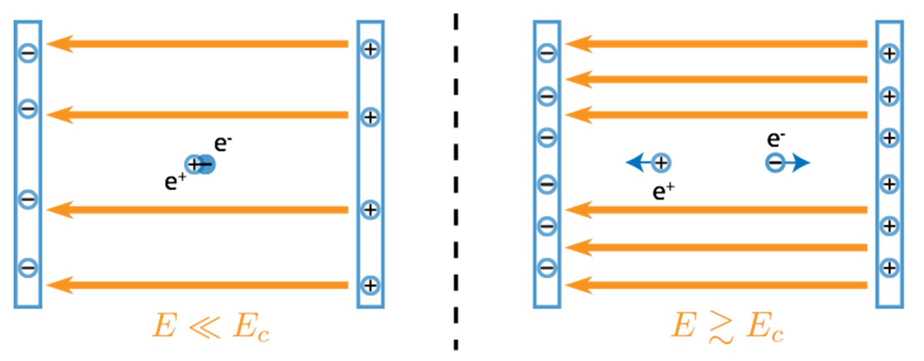
- Gauge theories are fundamental to Standard Model of High-Energy Physics (HEP). They are built up of fermionic and bosonic particles, which represent matter field and force carriers respectively.
- Requirements to simulate a HEP process using atomic systems:
  1. Work with finite dimensional Hilbert 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 $P = exp\left(-\pi \frac{E_c}{E}\right)$

Critical field strength, $E_c = \frac{m_e^2 c^3}{\hbar e} \approx 10^{18}\, Vm^{-1}$

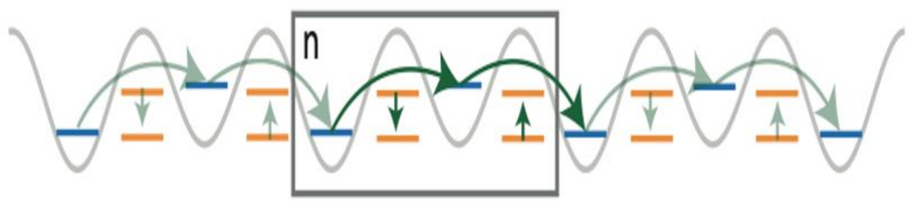
$I_c \approx 10^{29}\, Wm^{-2}$

Can we construct a quantum simulator?

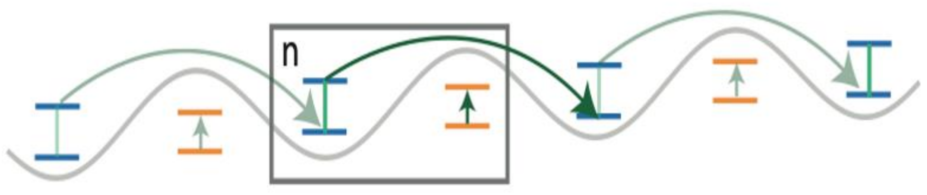
QED in 1+1 D

- **Quantum link model:**
  - Gauge fields are replaced by quantum mechanical spins $\hat{L}_n$.
  - A discrete 'Electric field' is represented by $\hat{L}_{n,z}$.
- **Formulation of U(1) gauge theories for cold atoms:**

A. Kogut -Susskind formulation: A staggered lattice
J. Kogut and L. Susskind, Phys. Rev. D 11, 395 (1975).
Kasper et al., NJP **19**, 023030 (2017)

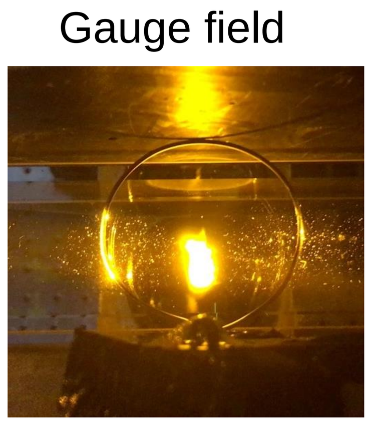


B. Wilson formulation: A tilted lattice
T.V. Zache et al. Quantum Sci. Technol. 3 034010 (2018)



- **Experimental implementation with atomic mixtures:**
  Alexander Mil et al. arXiv:1909.07641(2019)

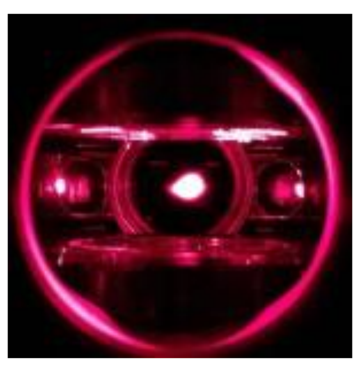
Gauge field



Sodium

+

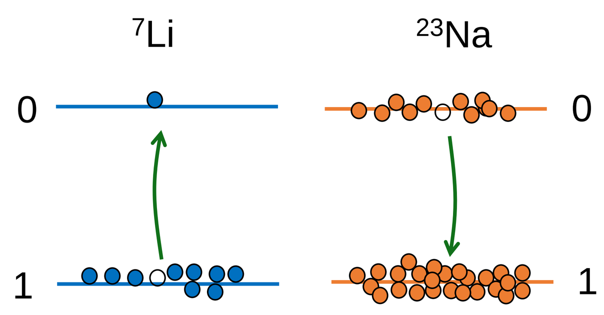
Matter field



Lithium

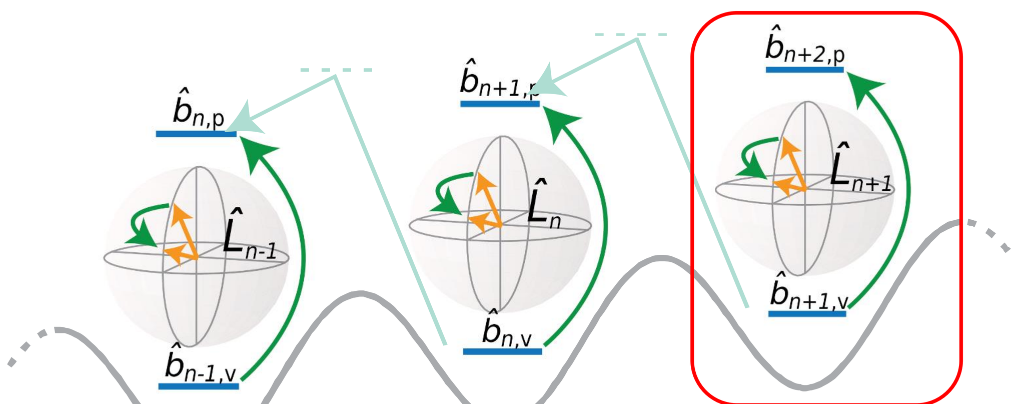
+

Gauge coupling

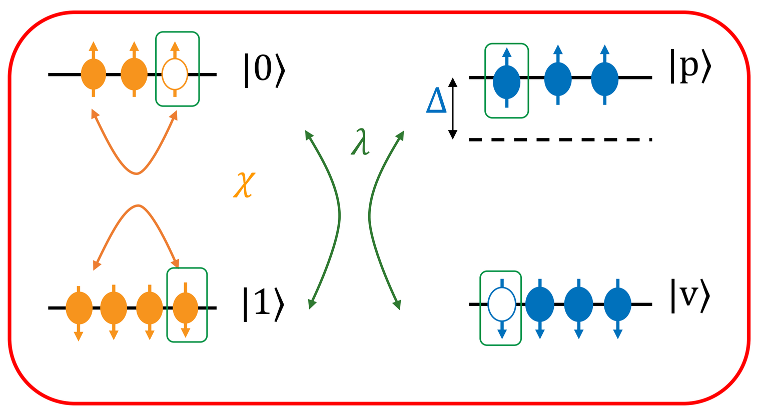


Spin changing collisions

- **U(1) gauge theory in 1D** $H = \sum_n [H_n + \hbar\Omega(\hat{b}^\dagger_{n,v}\hat{b}_{n+1,p} + h.c)]$



Building block



U-J. Wiese, 10.1002/andp.201300104

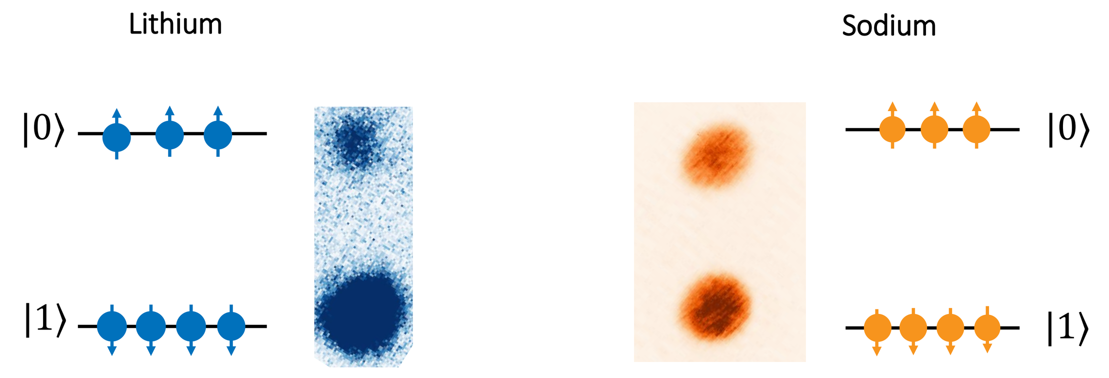
$$H_n = \chi L_{z,n}^2 + \frac{\Delta}{2}(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v) + \lambda(\hat{b}_p^\dagger \hat{L}_- \hat{b}_v - \hat{b}_v^\dagger \hat{L}_+ \hat{b}_p)$$

Gauge field — Matter field — Gauge coupling

Related works: Görg et al. Nature Physics, volume 15, 1161-1167(2019)
Schweizer et al. Nature Physics, volume 15, 1168- 1173(2019)

Initial state preparation

- **Condensing ^{23}Na and ^{7}Li to quantum degeneracy:**

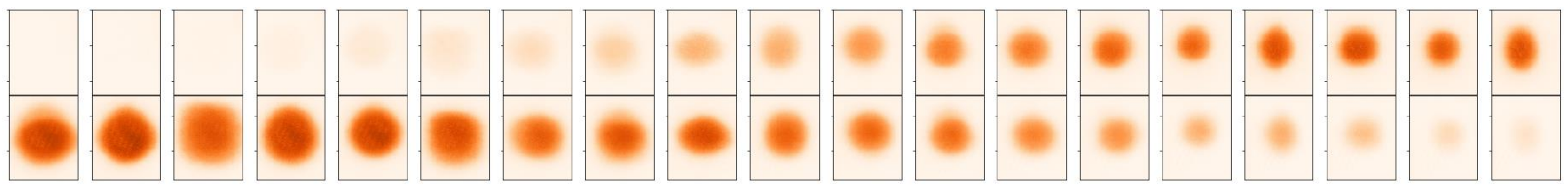


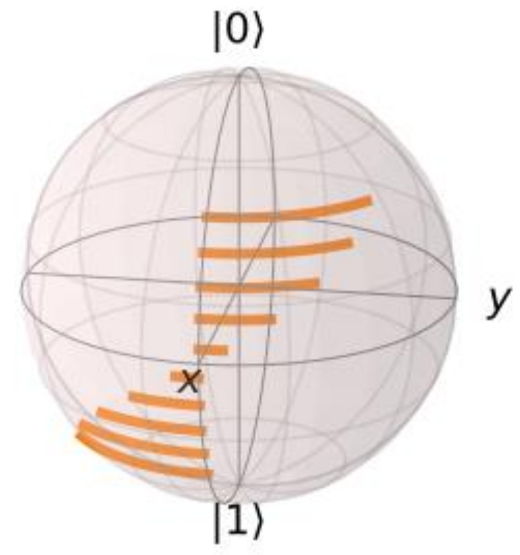
$N_{Na} = 300 \times 10^3$

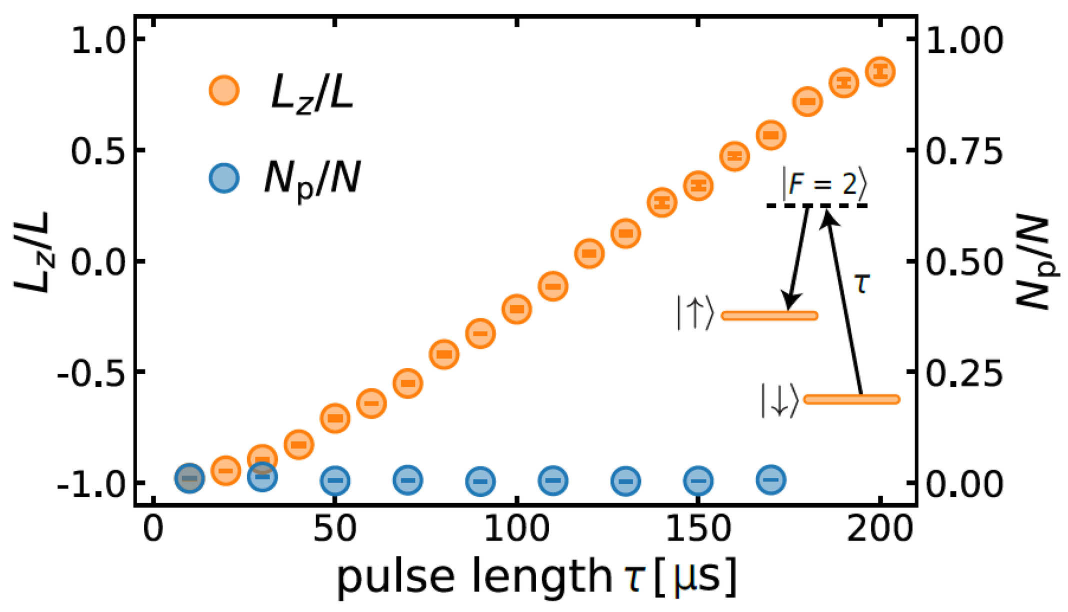
$N_{Li} = 50 \times 10^3$

Offset magnetic field ~ 2G

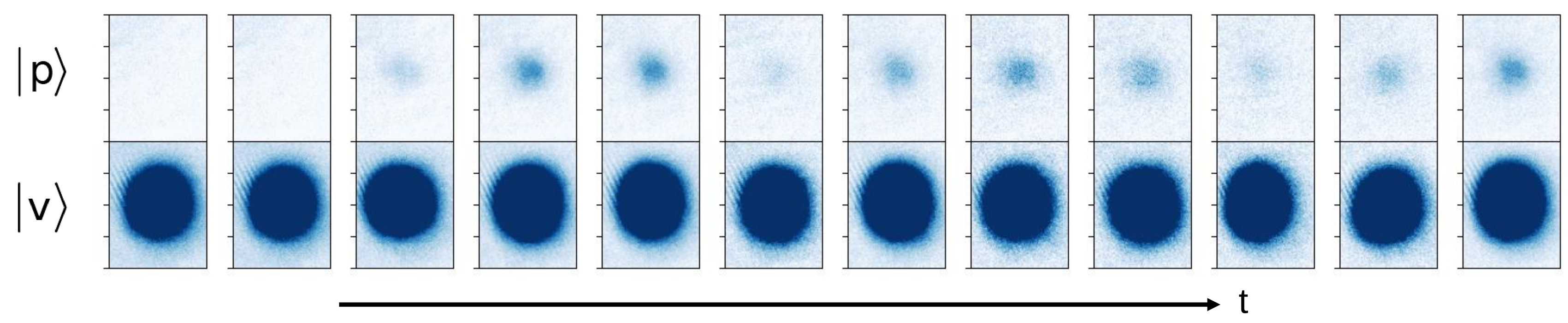
- **Preparing coherent superposition of internal states in ^{23}Na:**

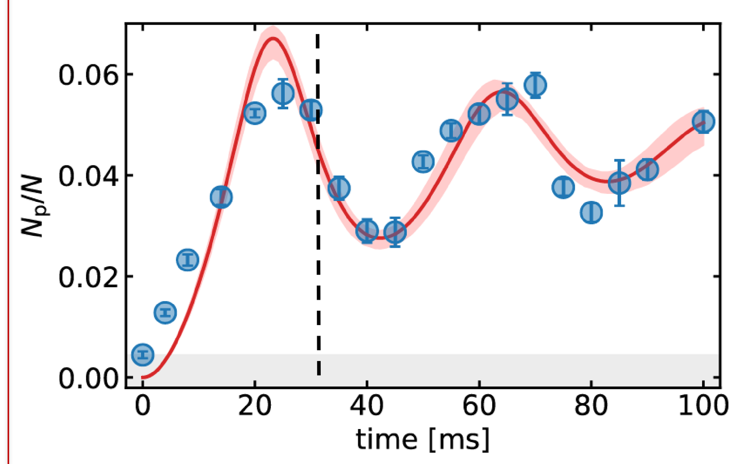






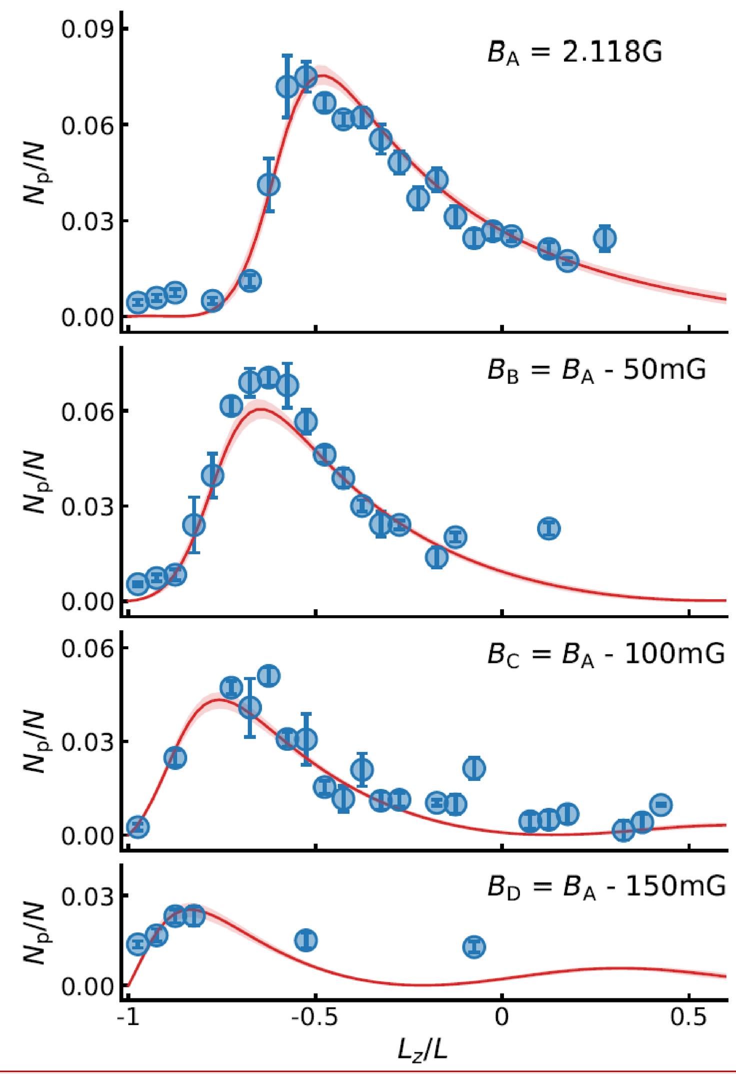
- **Dynamics of particle production:**





- **Spin changing collisions(SCC)**: Up to 6% of the total number of ^{7}Li atoms are transferred from the "vacuum" state to the"particle" state after the quench.
- The theoretical mean-field predicition of the Hamiltonian(red curve) is obtained by the model parameters χ, Δ, λ.

- **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:

$$2\chi L_z \sim \Delta$$

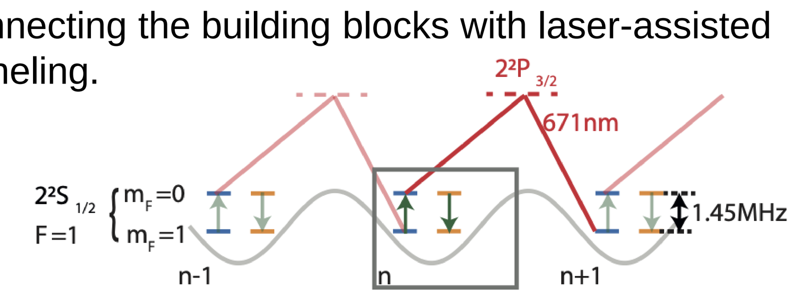
- Changing the external magnetic field changes Δ.

$$\Delta(L_z, B) = \Delta_0 + \Delta_L L_z + \Delta_B (B - B_A)/B_A$$

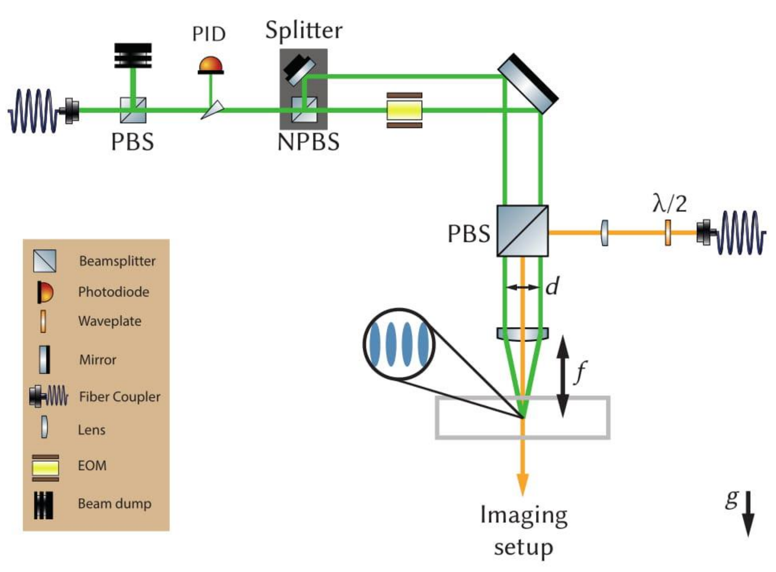
- Total magnetization is conserved.
- Particle production is not observed for fields smaller than B ~ 1.96 G as the matter and the gauge field become too far off-resonant.

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.



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