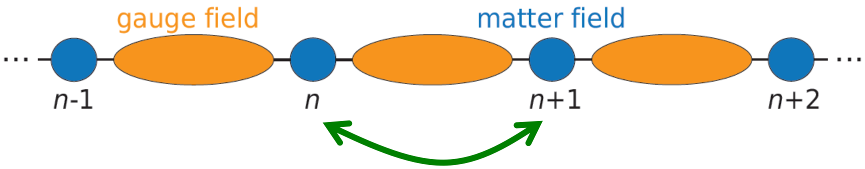
Quantum simulation of dynamical gauge fields using ultracold atomic mixtures

Apoorva Hegde, Alexander Mil, Torsten Zache, Andy Xia, Rohit Bhatt, Markus Oberthaler, Philipp Hauke, Jürgen Berges, Fred Jendrzejewski
Kirchhoff- Institut für Physik, Im Neunheimer Feld 227, 69120 Heidelberg, Germany
apoorva.hegde@kip.uni-heidelberg.de

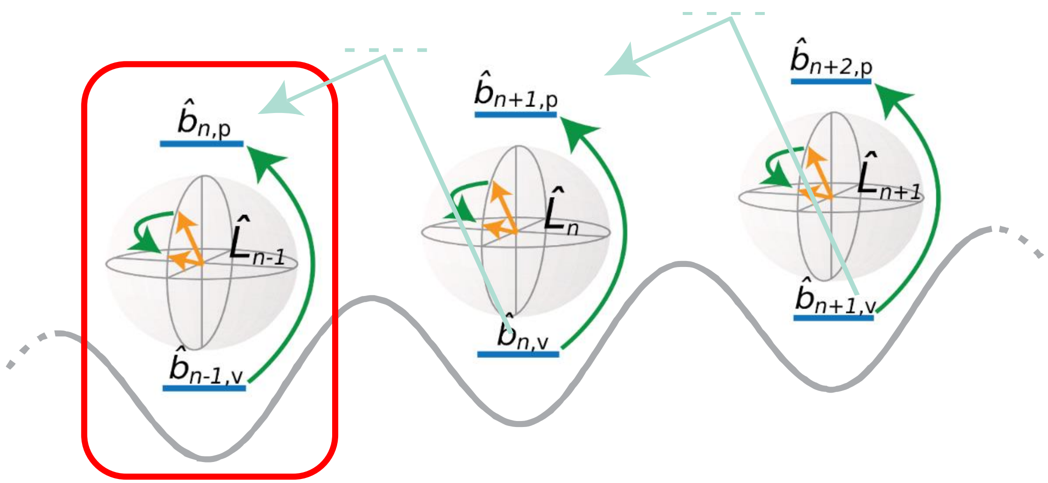
U(1) gauge theory with cold atoms



Related Theory: Uwe- Jens Wiese, Ann. Phys. (Berlin) 525, No. 10–11, 777–796 (2013)
Zohar et.al, PHYSICAL REVIEW A **88**, 023617 (2013)

Similar experimental works: Schweizer et al. arXiv: 1901.07103 (2019)
Görg et al. Nature Physics (2019)

- Fermions(matter), bosons(gauge field), and local gauge invariance
- High Energy Physics ⟶ Quantum gas mixtures
  - Gauge fields are replaced by quantum mechanical spins $\hat{L}_n$.
  - A discrete 'Electric field' is represented by $\hat{L}_{n,z}$.



$$H = \sum_n \left[H_n + \hbar\Omega\left(\hat{b}^\dagger_{n,v}\hat{b}_{n,p} + h.c\right)\right]$$

H_n: hamiltonian of the building block.

Ω : Coupling strength between the two matter states.

$\hat{b}^\dagger_{n,v}, \hat{b}_{n,p}$: creation and annihilation operators for 'vacuum' and 'particle' states.

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Juniorprofessorenprogramm MWK Baden-Württemberg
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Gauge field

Sodium

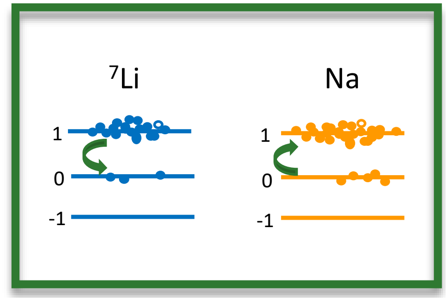
+

Matter field

Lithium

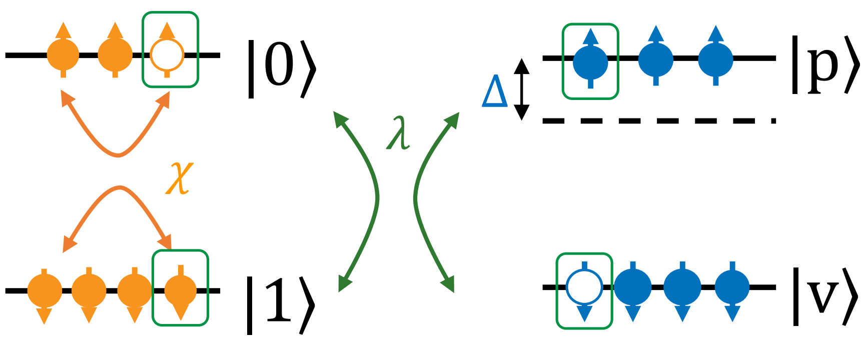
+

Gauge coupling



Spin changing collisions

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



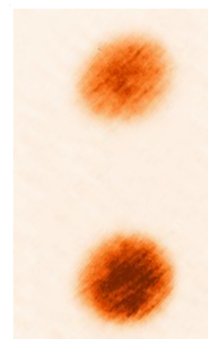
$N_{Na} \approx 300 \times 10^3$

$\omega_{Na} = 2\pi \times 200$ Hz

$N_{Li} \approx 30 \times 10^3$

$\omega_{Li} = 2\omega_{Na}$

Sodium

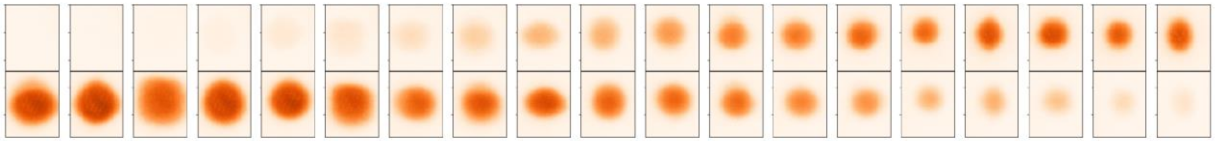


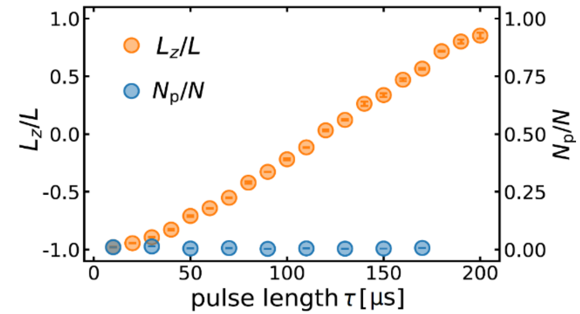
Lithium

$B \approx 2$ G

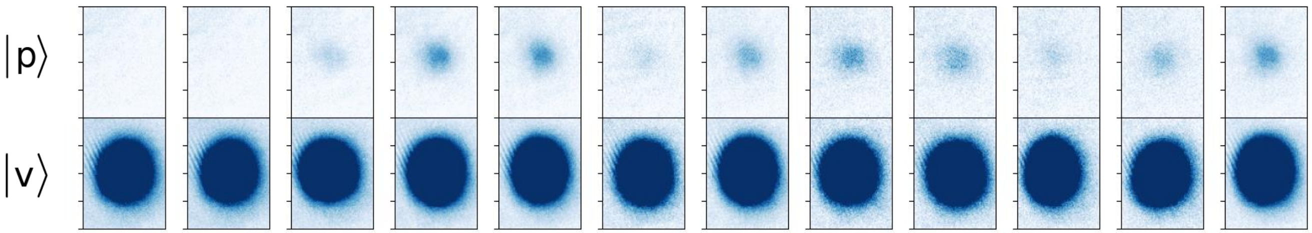
Initial state preparation and dynamics

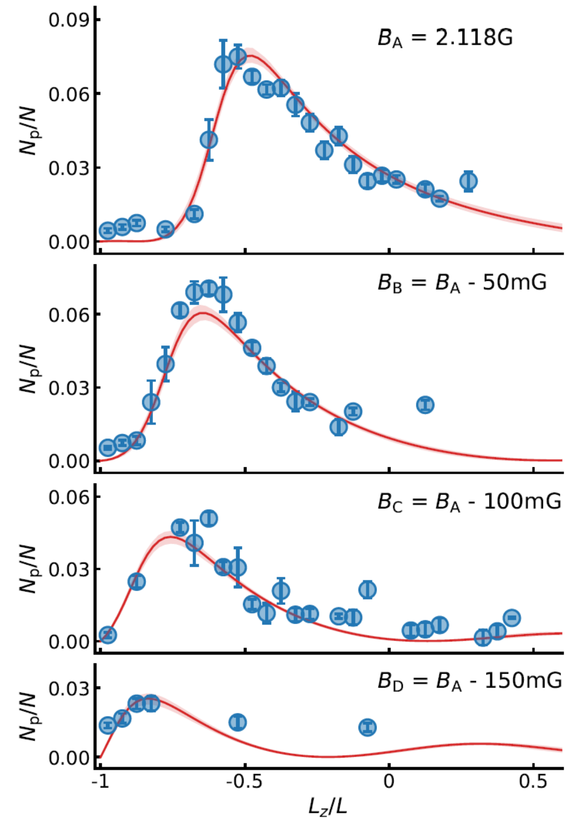
Create a coherent superposition in Sodium:



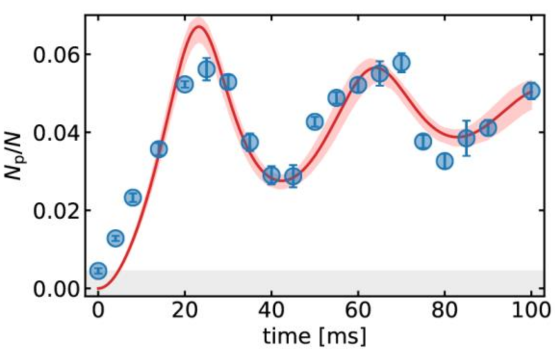


Observed dynamics: Spin transfer in Lithium

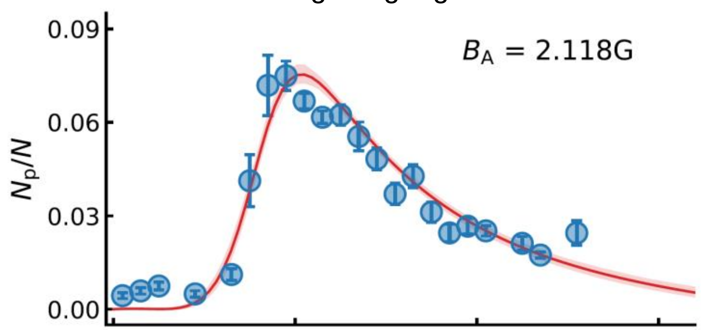




Scanning the interaction time

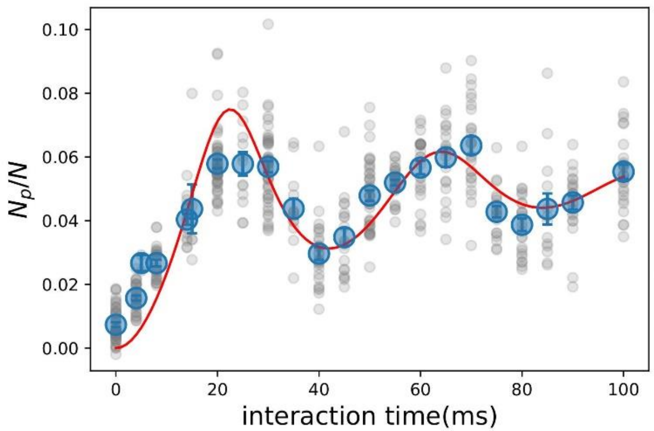


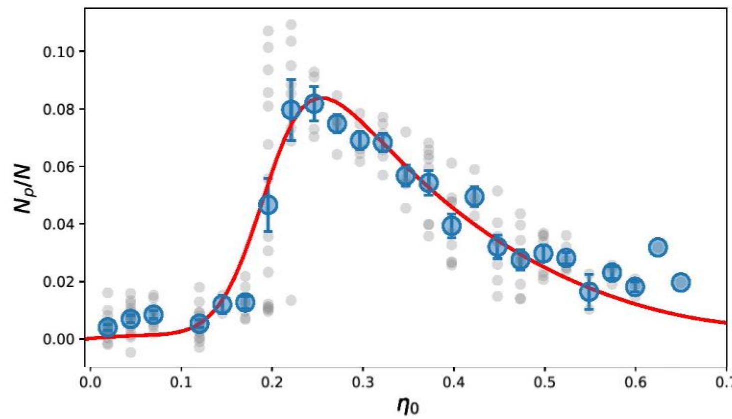
Scanning the gauge field



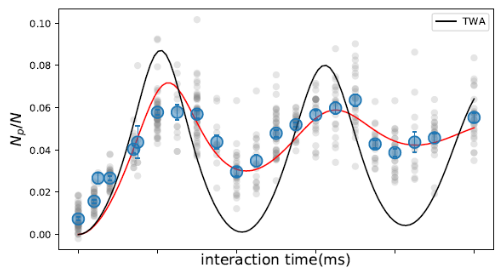
$$H_n = \chi L_{z,N}^2 + \frac{\Delta}{2}(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v) + \lambda(\hat{b}_p^\dagger \hat{L}_- \hat{b}_v - \hat{b}_v^\dagger \hat{L}_+ \hat{b}_p) + \text{decoherence}$$

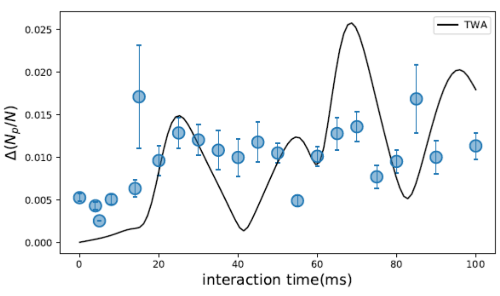
Nature of the fluctuations observed in the data

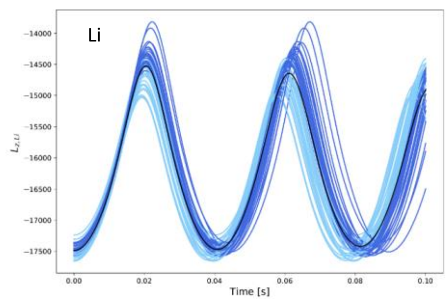


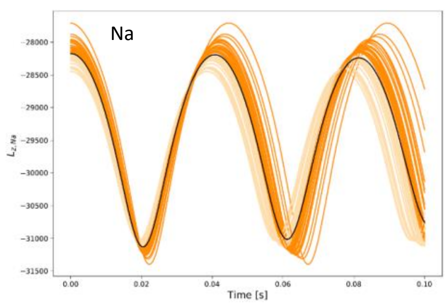


Truncated Wigner Approximation









- Fluctuations in the initial state
- Randomly selecting an initial state from Gaussian distribution
- Incorporate uncertainty in L_z of Sodium

<u>Projection noise of Sodium is seen in Lithium transfer</u>