Generation and Detection of Atomic Spin Entanglement in Optical Lattices

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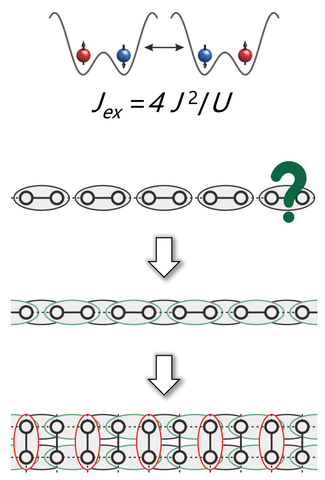
Motivation

Towards Scalable Quantum Computing



Ultracold atoms in an optical lattice have excellent coherence properties and can be manipulated in parallel. It is attractive to create resilient entangled states for measurement-based quantum computation in optical lattices*.

Although the entangled spin pairs can be created during the dynamical evolution of spin pairs driven by exchange interactions§, it was not possible to directly verify the entanglement by measuring the spin correlations until now.

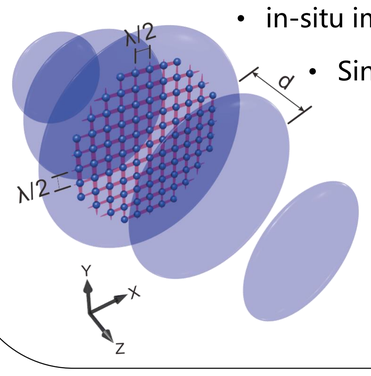
Experimental Setup

arXiv : 1507.05937

$V(x) = V_{xs}Cos^2(2kx) + V_{xl}Cos^2(kx)$

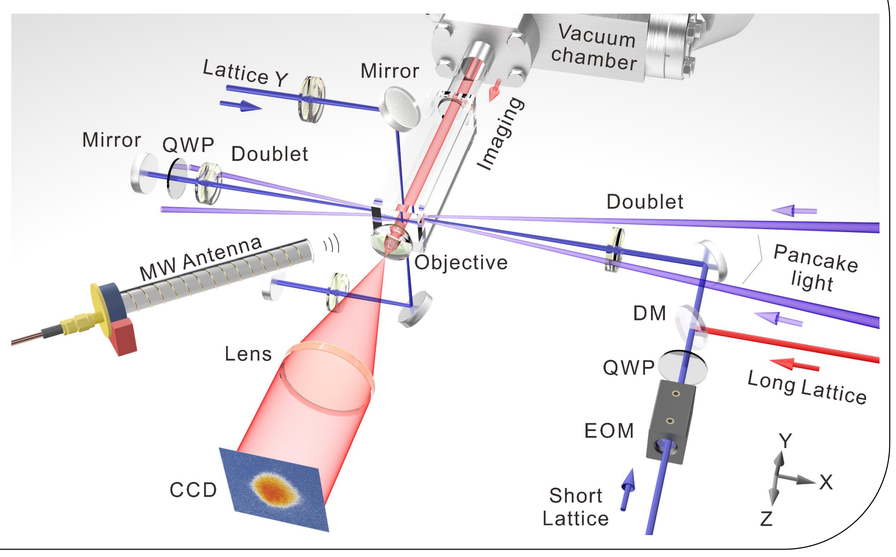
$V(y) = V_{ys}Cos^2(2kx)$

$V(z) = V_z Cos^2(2k_z x)$



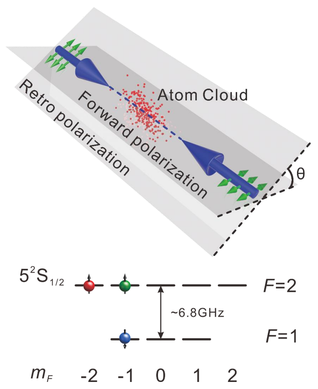
- in-situ imaging (N.A.=0.48)
- Single layer of atoms

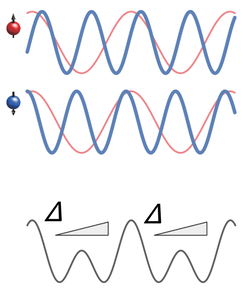
^{87}Rb
$\lambda_s = 767\ nm$
$\lambda_l = 1534\ nm$
$d = 4\ \mu m$



Spin-dependent Addressing

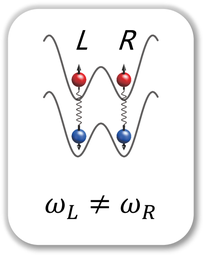
- **Spin-dependent Superlattice**

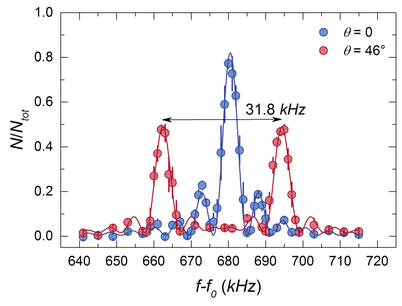




- **Effective Local Gradient *B* Field**

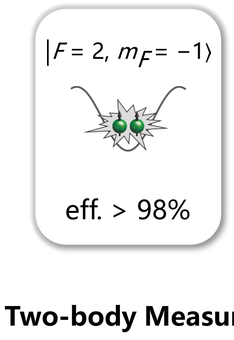
- **"Site-Resolved" Addressing**

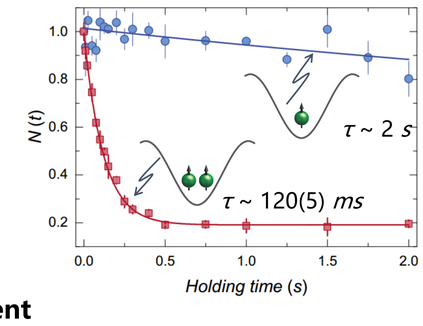




Two-body State Detection

- **Hyperfine changing collisional loss**





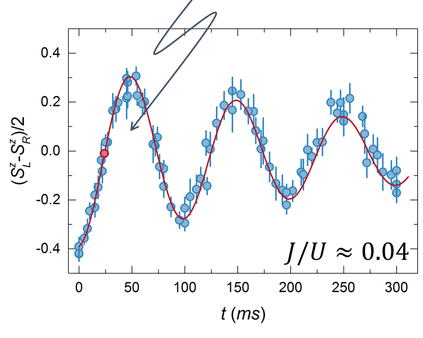
Two-body Measurement

Generating Spin Entanglement

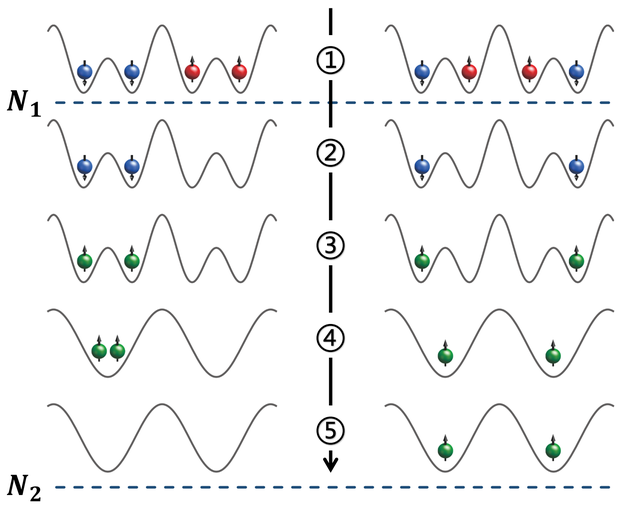
- **$\sqrt{\text{SWAP}}$ - gate**

First initializing the system from a Mott filling state $|\downarrow,\downarrow\rangle$ to $|\downarrow,\uparrow\rangle$, then letting the system evolve a quarter period of superexchange process,

$$|\downarrow,\uparrow\rangle \Longrightarrow \frac{|\downarrow,\uparrow\rangle + i|\uparrow,\downarrow\rangle}{\sqrt{2}}$$



- **Two-Step Filtering Sequence**

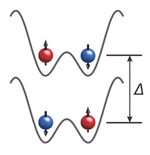


① Imaging $|\uparrow\rangle$, get N_1; ② $|\uparrow\rangle \Rightarrow |\uparrow'\rangle$ by adiabatic passage;

③ Merging double wells; ④ Two body collisional loss;

⑤ Imaging rest atoms, get N_2.

- **Control Entangled Phase**



$$\frac{|\downarrow,\uparrow\rangle + e^{i\phi(t)}|\uparrow,\downarrow\rangle}{\sqrt{2}}$$

$$\phi(t) = \phi_0 + \Delta\, t/\hbar$$

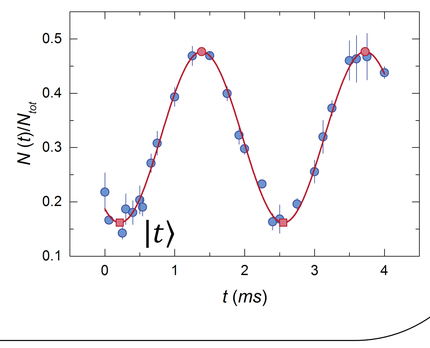
$$|t\rangle = \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle + |\uparrow,\downarrow\rangle) \overset{\pi/2}{\Longrightarrow} \frac{1}{\sqrt{2}}(|\downarrow,\downarrow\rangle + |\uparrow,\uparrow\rangle)$$

$$|s\rangle = \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle - |\uparrow,\downarrow\rangle) \overset{\pi/2}{\Longrightarrow} |s\rangle$$

Singlet-Triplet Oscillation

$$|t\rangle \overset{\pi/2}{\Longrightarrow} \overset{TSFS.}{\Longrightarrow} 0$$

$$|s\rangle \overset{\pi/2}{\Longrightarrow} \overset{TSFS.}{\Longrightarrow} \frac{N_{tot}}{2}$$



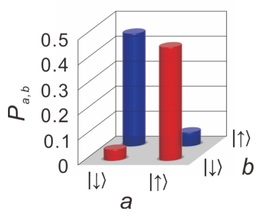
Detecting Spin Entanglement

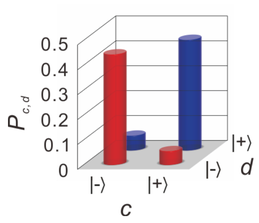
- **Measuring Spin Correlations**

$$P_{\downarrow\downarrow} = \frac{N_{tot} - N_1 - N_2}{N_{tot}}$$

$$E_{zz} = \langle \sigma_L^z \otimes \sigma_R^z \rangle = P_{\uparrow\uparrow} - P_{\uparrow\downarrow} - P_{\downarrow\uparrow} + P_{\downarrow\downarrow}$$

$$E_{yy} = \langle \sigma_L^y \otimes \sigma_R^y \rangle = -P_{++} + P_{+-} + P_{-+} - P_{--}$$



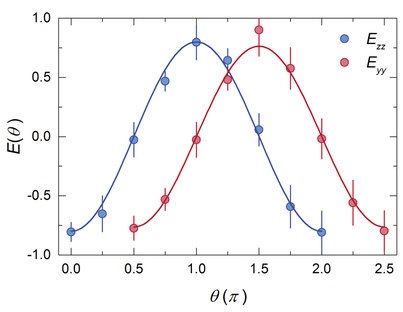


- **Lower bound of Fidelity**

$$F \geq -(E_{zz} + E_{yy}) = 0.79(6)$$

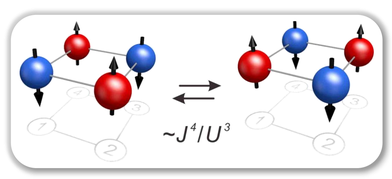
- **Violation of Bell's inequality**

$$S = 2.21 \pm 0.08 > 2$$



Outlook

- Extending to two-dimensional spin-dependent superlattices;
- Measuring Four-Spin Ring-Exchange interactions† $S_1^x S_2^x S_3^x S_4^x$;
- Simulating a minimal instance of Toric code model‡;



arXiv : 1602.05709

- Scaling up the two-dimensional quantum states; ...

Funding

Reference:

* B. Vaucher, et. al. New J. Phys. 10, 023005 (2008).
§ S. Trotzky, et. al. Science, 319, 295 (2008).
† B. Paredes and I. Bloch, Phys. Rev. A. 77, 023603 (2008).
‡ A. Y. Kitaev, Ann. Phys. 303, 2 (2003).