Available Positions

Dr. Poul Jessen, University of Arizona (ITP 9-13-01)
Quantum Control in Optical Lattices: First Steps Toward Quantum Logic With Trapped Atoms.

- Quantum Control in Optical Double Wells
- Quantum Logic in Optical Lattices
- Measuring a spin density matrix
- Quantum State Reconstruction
- General Ideas
- Coherent tunneling & "Schrödinger Cats"
- Quantum vs. classical physics (chaos)

Postdoc Positions

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Poul Jessen
Quantum Control in Optical Lattices: First Steps

Can we perform entangling operations?

Quantum gates

Advantages
- Weak coupling to environment
- Good neutral atom traps
- Laser cooling
- Quantum control
- Much like ion trap qubits

Disadvantages
- Weak coupling between atoms

Neutral Atom Quantum Logic

Bring qubits together

Encoding qubits

Encoding qubits with neutral atoms

Quantum Information Processing
Dr. Poul Jessen, University of Arizona (ITP 9-13-01) Quantum Control in Optical Lattices: First Steps

Good qubit encoding

- scalar potential + effective magnetic field

\[ \frac{1}{2} \left( (x \cdot \mathbf{E})_0 \right)_0 - \frac{1}{2} \left( (x \cdot \mathbf{B})_0 \right) = (x \cdot \mathbf{f}) \]

Optical Potential = \( -d \cdot \mathbf{E}(x) \)

Light Shift of Alkali Atoms

Neutral Atom Traps

\[ \text{Neutral trap} \]

\[ \text{Ion trap} \]

\[ \text{Comparison} \]

\[ \text{Magnetic dipole} \]

\[ \text{Electric dipole (optical)} \]
Preparing a Quantum State in the Lab

Optical Lattice Traps

S. E. Harnett et al., PRX 9, 041029 (2019)
Moving qubits in 3D lattices

Design Lattices
Broader Perspective

Quantum state preparation, control & measurement in complex quantum systems
- Fundamental interest
- Resource for new technology

Paradigm
quantum coherent evolution & control
- micro- to mesoscopic
  - action $x_0p_0 = 0.1-20 \hbar$
- complex:
  - motion & spin entangled
  - classical chaos
- powerfull toolbox:
  - state preparation, control & measurement

Optical Double-Well Potentials

Spin-1/2 atom 1D lin–θ–lin lattice

$B_{\text{loc}} \propto \sigma_\theta \Rightarrow No coupling!$

External magnetic field

$B_c \neq 0$

$B_\perp \neq 0$
Coherent Tunneling of Spinor Wavepackets

**Preparation**

- Tunneling $\leftrightarrow$ precession of spin
- entangled spin & space degrees of freedom

**Rabi oscillation**

- Spin-1/2 system coupled to harmonic oscillator
- Jaynes-Cummings or spin-boson problem

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**Real (Cesium) Atoms**

1D lin–80°–lin

$U(z)$

Cs ($F = 4$), $\Delta >> \Delta_{HFS}$

- much like simple atom -
Experiment

Haycock et al., PRL 85, 3365 (2000)

1D in-plane lattice

"Zeeman microscope"

- precool (laser cooling)
  - load into optical lattice
    \( \Delta = -300 \text{C} \)
  - select ground state
    - pump into \( m = 4 \) (left well)

Stern-Gerlach analysis

TOF signal (arb. units)

\[ \langle \psi| \hat{A} |\psi \rangle \]

Detection

Intersecting spinor wavepackets

\[ \Psi \sim 5 \times 10^{-2} \text{cm}^{-1} \]

Characteristic length

\[ \Psi_{\text{Kohn}} \sim 3 \text{nm} \]

Schrodinger quantum coherence

mesoscopic

Typical bandstructure

\[ \langle \psi| \hat{A} |\psi \rangle \]

\[ \langle \psi| \hat{A} |\psi \rangle \]

\[ \langle \psi| \hat{A} |\psi \rangle \]

\[ \langle \psi| \hat{A} |\psi \rangle \]

Localised states

Bloch spinors

\[ \psi \sim 5 \times 10^{-2} \text{cm}^{-1} \]

\[ \Psi_{\text{Kohn}} \sim 3 \text{nm} \]

D. Poul Jessen, University of Arizona (ITP 9-13-01) Quantum Control in Optical Lattices: First Steps
Tunneling Rabi Oscillations

- Coherent dynamics
- Dephasing due to inhomogeneity

\[ \tau_{\text{exc}} = 303 \, \mu\text{s} \]
\[ \tau_{\text{damp}} = 335 \, \mu\text{s} \]

**Average Magnetization**

\[ \langle m \rangle \]

\[ t (\mu\text{s}) \]

**Center-of-Mass**

(Theory)

**Magnetic Populations**

(Theory)

(Experiment)

\[ \rho(k,z) \]

\[ \pi_m \]

- excellent quantitative agreement
- characteristic

\[ \Omega_R = \sqrt{\Omega_x^2 + \Omega_z^2} \]

dependence of 2-level system

Tunneling Rabi frequency: theory vs. experiment

- vs. depth

\[ \Omega_R / E_R \]

\[ U_1 / E_R \]

- no free parameters
- 4% underestimate of depth

- vs. \( B_x \)

\[ \Omega_R / E_R \]

\[ B_x (\text{mG}) \]

- vs. \( B_z \)

\[ \Omega_R / E_R \]

\[ -B_z \text{ (mG)} \]
Quantum vs. Classical Dynamics

- Observables diverge rapidly
- Classical trajectories
- Chaos

Is this Quantum Tunneling?

- Above barrier motion?
- Spin state cannot follow changing polarization

Quantum Picture

Classical Picture

Particle w/magnetic moment in trap + magnetic field
\( \vec{\mu} \) cannot follow changes in \( B(z) \)
Quantum State Reconstruction

**Motivation:** Better tools to track evolution of spinor wavepackets in optical lattices can now allow for measuring full density matrix of trapped atomic systems. Magnetic populations alone do not distinguish this.

**Solution:** Explicit knowledge of spin coherence in atomic wavepackets could be used as a meter for center-of-mass motion.

- State reconstruction in analogy to light fields.
- Mössbauer molecular vibrations.
- Motion of trapped ions coupled via spins.
- NMR photon pairs.

**Quantum Feedback:**
- Optimal control?
- Heisenberg?
- How to implement it?
- Current diagnostic adequate?
- Experimental signature?
- How to study quantum/classical transition in the laboratory?
- By continuous measurement?
- By adding decoherence?
- By recovering classical dynamics?

**Where to go with this?**

Quantum/classical transition in chaotic systems an outstanding issue.
Spin-1/2: density matrix constraints 3 indep. real numbers
\[ \rho = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix}, \quad Tr \rho = 1, \quad \rho = \rho^\dagger \]
\[ \rho_{11}, \quad \text{Re}[\rho_{12}], \quad \text{Im}[\rho_{12}] \]

Stern-Gerlach measurement:

\[ \hat{S}_z \rightarrow \rho_{11}, \rho_{22} \]
\[ \hat{S}_x \rightarrow \text{Re}[\rho_{12}] \]
\[ \hat{S}_y \rightarrow \text{Im}[\rho_{12}] \]

Note: can equally well rotate system 3 ways & measure \( \hat{S}_z \).

Large Angular Momenta

Cesium: \( F = 4 \) ground hyperfine manifold

Measure: \( \hat{F}_z \) (2F+1 = 9 populations)

use 4F+1 = 17 geometrical rotations

Each rotation:

\[ \rho^{(\theta, \varphi)} = \hat{R} \rho \hat{R}^\dagger \]
\[ \hat{R} = \hat{R}(\theta, \varphi) \]
\[ \rho_{ii} = \sum_{j,k} R_{ij} R_{ik} \rho_{jk} \]

4F+1 rotations \( \Rightarrow \) linear system is invertible
Stern-Gerlach Analysis of Laser-Cooled Atoms

well separated arrival times

Quantum State Reconstruction

Test with known input states
(Cs $6S_{1/2}(F=4)$ ground state)
What does it mean when this Wigner function is negative?

A state that is not quasi-classical

Measured Wigner Function for $|\phi, 0\rangle$

Precession of a Spin-Coherent State

Angular Momentum Wigner Functions

$A_{\theta}^{\phi}(\theta, \phi)$; Dzurak & Sorensen (1994)
Outlook

Quantum Information Science
Based on laser traps & lattices
- Ties into other "quantum technologies"
- Experimental capabilities
- Will continue to develop
- Clean laboratory realization
- Very rich physical system

Quantum State Reconstruction
Near maximally mixed state (3D optical molasses)