Properties of Fermionic and Bosonic Optical Lattice Clocks

A Scheme for a Bosonic Magnesium Optical Clock
• Optical clocks with Fermions and Bosons
  – Properties, clock transition, excitation
• Systematics
  – Magnetic fields, clock laser, lattice, collisions
• Bosonic Magnesium Optical Lattice Clock
  – Current setup and possible future scheme
• Conclusion
Optical Clocks

• Spectroscopy of narrow transition
  – Alkaline-Earth (like): Mg, Sr, Yb, Hg,…
  – Intercombination line $^1S_0 \rightarrow ^3P_0$
    • Completely forbidden for Bosons
    • Weakly allowed for Fermions

• Spectroscopy in optical lattice
  – Vanishing first order Doppler- and recoil-shift (Lamb-Dicke)
  – Lattice must be operated at magic wavelength
Properties

Bosons

Nuclear spin $I = 0$
- No magnetic substates
  - Only second-order Zeeman
- External bias field necessary to allow the clock-transition
  - Linewidth tuning
- Insensitive to lattice polarization

Fermions

Nuclear spin $I = n/2$
- Magnetic substates
  - First- and second-order Zeeman
  - Line-pulling
- Hyperfinemixing of $^3P_1$ into $^3P_0$
  - $\mu$Hz-mHz linewidth
- Sensitive to lattice polarization
  - Vector- and tensor-shift
  - Polarization gradients in 3D-lattice configuration

s-Wave Scattering
- Precise density control necessary
- $\rightarrow$ Single-site occupation

Scattering suppressed
- No s-wave, only higher order

Magnetic Sensitivity

Magnetic field induced spectroscopy

Mixing field: In the order of 10 G
- Second-order Zeeman: ~ 10 - 100 Hz
  - For 10^{-17}: B-Field stability of 10^{-4} – 10^{-5}
Field calibration $^1S_0 \rightarrow ^3P_1$
- But $^3P_1$ sensitive to lattice polarization!

Weak bias field to decouple $m_F$ states

Bias field: ~100 mG
- First-order Zeeman: ~ 10 - 100 Hz
  - Interleaved measurements of $\pm m_F$ and averaging mostly gets rid of shift
- Second-order Zeeman: ~ 10-100 mHz
  - Characterized by interleaved measurements and taking difference

Spectroscopy Induced Shifts

**Bosons**

Magnetic field induced spectroscopy

High laser intensities necessary: mW/cm² – W/cm²
- Considerable high light-shifts ~ 1-10 Hz
  - For $10^{-17}$: Intensity stabilization: $10^{-3}$-$10^{-4}$

**Fermions**

Line-pulling

Low laser intensities: µW/cm²
- Low light-shifts < mHz

Residual population → asymmetric background
- State preparation crucial

Probelaser polarization
- Coupling to neighbouring $m_f$ states
- Birefringence (viewports), alignment to bias field

Lattice Induced Shifts

**Bosons**

Besides tunneling (see my talk from the last workshop)...

**Hyperpolarizability**

Higher-order dependence on lattice-depth $U_0$

e.g. 2 photon resonances [1]

- Can be evaluated. No serious barrier for $10^{-17}$ or below.

**Magnetic Dipole (M1), Electric Quadrupole (E2)**

E1 lattice potential: $U_{E1} = -E_1(\lambda, I) \cos^2(kz)$

Additional M1/E2 term $U_{M1/E2} = [M_1(\lambda, I) + E_2(\lambda, I)] \sin^2(kz)$

Scaling: $\sqrt{I}$, fractional shift: $< 10^{-17}$ [2,3]

**Fermions only:**

Vector and tensor shift (nuclear spin, sensitive to lattice polarization)

$$\Delta n^{E1} = (\Delta \kappa' \xi + \Delta \kappa'' m_F \xi e_k \cdot e_B + \Delta \kappa' \beta) U_0$$

with $\beta = (3|\vec{e} \cdot \vec{e}_B|)^2 - 1)[3m_F^2 - F(F+1)]$

Systematic evaluation with interleaved $m_F$ (like Zeeman): $<10^{-17}$

Linear lattice polarization + orthogonal bias field minimize vector-shift

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Klaus Zipfel

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Collisional Shifts

Bosons

Background gas collisions (Fermions & Bosons)
Besides scattering losses: Phase-shift of states [1]
• Density estimation (H,H₂,He,Xe,...) over trapping lifetime
• Then: Shift estimation over $C_6$ coefficients [1] $< 10^{-17}$

Bunching $< n(e) > = \frac{1}{e^{\beta(E-)}-1}$

s-wave scattering even at $T = 0$
• Solution: single-site occupation (e.g. 3D lattice)

Fermions

Anti-Bunching $< n(e) > = \frac{1}{e^{\beta(E-)}+1}$

s-wave supressed (for indistinguishable fermions)
• Spin-polarization of atomic sample
• Purification of initial state
  – Minimize inhomogenities for excitation

## Conclusion

### Magnetic fields

- **Bosons:** High for allowing clock-transition
  - Second-order Zeeman shift high
- **Fermions:** Moderate for lifting degeneracy of $m_F$'s
  - Interleaved $m_F$ measurement
    - First-order Zeeman averages out
    - Second-order Zeeman by taking difference
    - 2x higher Dick-Effect

### Spectroscopy induced shifts

- **Bosons:** High AC-Stark for allowing clock-transition
- **Fermions:** Low AC-Stark
  - Line-pulling due to $m_F$s

### Lattice induced shifts

- **Bosons:** Only hyperpolarizability and M1/E2
- **Fermions:** Additional vector and tensor shifts (polarization)

### Collisions

- **Bosons:** s-wave scattering dominant $\rightarrow$ single-site occupation
- **Fermions:** s-wave effectively suppressed

### Reduction of spectroscopic shifts:

- Interferometric schemes e.g. Hyper-Ramsey
  - Precise Ramsey-pulse synthesis allows significant reduction of sensitivity to spectroscopy AC-Stark
  - Turning of magnetic fields during free evolution time reduces magnetic field sensitivity

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**Generalized Ramsey scheme** with non-linear sensitivity to shifts during pulses

**Pulse conditions:**
1) \( \Omega_0(\tau_1 + \tau_2) = 2\pi n \)
2) \( \Omega_0\tau_1 = \pi(2m + 1)/2 \)
\( \Rightarrow \frac{\tau_2}{\tau_1} = \frac{(4n - 2m - 1)}{(2m + 1)} \)

E.g. \( \tau_1 = \pi/2 \), \( \tau_2 = \pi 3/2 \)

Effective shift \( \Delta = \Delta_{sh} - \Delta_{\text{step}} \)

**Properties:**
- Shifts during pulse separation time \( T \) are absent (no clock-Laser) or can be turned off (magnetic fields).
  \( \Rightarrow \) Free evolution of atomic phase
- Nonlinear behaviour of effective shifts during pulses
  \( \Rightarrow \) Moderate control of spectroscopy fields

**Example:** Bosonic \(^{174}\text{Yb} \), \( T=40\text{ms} \), \( \tau_1 = 10 \text{ ms} \) \( (\Omega/2\pi =25 \text{ Hz}) \) \( \Rightarrow 20 \text{ G} \text{ B-Field and AC-Stark of 70 Hz.} \)
  Control of AC-Stark to 0.7 Hz (percent level) results in shift of 0.35 mHz \( (10^{-18}) \)

**But:** If \( \Omega_0(\tau_1 + \tau_2) \) criteria not ideally matched: Again sensitive to shifts

Solution: \( \pi \) phase-shift during second Ramsey-Pulse.

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A Scheme for a Bosonic Magnesium Optical Clock
Atomic properties:
• Low sensitivity to black-body-radiation
  \(-3.9 \times 10^{-16}\)
• No known two-photon resonances near \(\lambda_{\text{Magic}}\)
  \(\rightarrow\) No Hyperpolarizability expected
• High MOT-temperatures
  – 3 mK S-MOT
  – 1 mK T-MOT
• Intercombination line does not allow for magneto-optical trapping

Current implementation
• Loading of the lattice
  – Density distribution in the lattice
• Spectroscopy

Future additions
• Hyper-Ramsey?
• Normalization scheme

on the next few slides
Direct loading of a lattice from a MOT not efficient

- mK Temperatures
- Density limited MOT
→ Only a small fraction can be transferred

Solution: Continuous loading of an optical trap from mK hot atoms [1]

- $^3P_0$ as dark state
- Continuous flux of mK-hot $^3P_0$ atoms
- Coldest can be accumulated in optical dipole trap
→ $10^5$ atoms at 100 µK

But:

- Not working for magic-Wavelength lattice
  - Ionization
- Adaptation to Fermion (I=5/2) → many more lasers

Transfer of atoms to the lattice:
- Loading of a dipole trap at 1064 nm
  10^5 atoms at 100 µK
- Transfer to optical lattice
  Up to 10^4 atoms at 10 µK
  Lamb-Dicke: 0.35
  Well-depth 55 µK (15 Er)

Density distribution in the lattice:
Atoms distributed over Rayleigh-range in 1064 nm dipole trap
\[ w_{0,1064} = 70 \mu \text{m} \Rightarrow b = 2z_0 = \frac{2\pi w_0^2}{\lambda} = 2.9 \text{ cm} \]
Magic Wavelength Lattice: \( \lambda_{\text{magic}} \approx 468.44 \)
\( \Rightarrow \) Lattice sites \( \frac{2.9 \text{ cm}}{468.44 \text{ nm}/2} \approx 124000 \)
With 10^4 atoms: 1 atom every 12 lattice sites
\( \Rightarrow \) Collisions suppressed

Preparation of $^1S_0$ atoms in lowest lattice band:
- Ramping down the lattice to $4\ E_r\ (\sim 14\ \mu K)$
- Remaining atoms at $T = 1.3\ \mu K$

**Magnetic field induced spectroscopy:**
Currently: $B = 100\ G$, $I = 7\ W/cm^2$
$\rightarrow\Omega = 2\pi \times 185\ Hz$
Detection with T-MOT (Background free)

**Huge shifts:**
- Clock-Laser: -3.5 Hz
- Quadratic-Zeeman: -21.7 kHz

Only for max. broadening for the search of the “magic wavelength”

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<th>Element</th>
<th>$\gamma$ [kHz]</th>
<th>$\Delta_{22}$ [THz]</th>
<th>$\alpha$ [Hz/($T\sqrt{mW/cm^2}$)]</th>
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Analyzing frequency-shift at different Trap-Depths and Lattice-Frequencies

\[ \lambda_{\text{magic}} \approx 468.44 \pm 0.27 \]
Magnetic field induced spectroscopy:

Rabi-Spectroscopy:
Low Rabi-Frequencies $\rightarrow$ Long pulses (Fourier-Limit)
$B = 1 \text{ G}, I = 1 \text{ W/cm}^2$
$\rightarrow \Omega = 2\pi \times 0.3 \text{ Hz}$

Moderate shifts:
- Clock-Laser: -0.5 Hz
- Quadratic-Zeeman: -2.17 Hz

To reach $10^{-17}$:
B-Field stability: $1.5 \times 10^{-3}$
Clock-Laser intensity stability: $1.2 \times 10^{-2}$

Hyper-Ramsey:
High Rabi-Frequencies $\rightarrow$ Shorter pulses
$B = 10 \text{ G}, I = 7 \text{ W/cm}^2$
$\rightarrow \Omega = 2\pi \times 8.2 \text{ Hz}$

High shifts:
- Clock-Laser: -3.5 Hz
- Quadratic-Zeeman: -217 Hz

B-Field stability: $1.5 \times 10^{-5}$
Clock-Laser intensity stability: $1.8 \times 10^{-3}$

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Reduction of Tunneling

**Tunneling in lattice:** (my last RTG talk, 2013)
- Line broadening and/or shift
- Reduces clock performance

**Solution:** Accelerated lattice ($\Delta E >$ Lattice band-width)
- Vertical lattice: $\Delta E = 138$ Hz
- With current setup: Tilting (up to 5°)
  $\Rightarrow \Delta E = 12$ Hz possible

**Currently:**
- Lattice depth: 15 Er ($\sim 55$ µK)
  $\Rightarrow$ Lattice band-width: few 100 Hz – 1 kHz
- MOPA to replace TiSa
- More efficient SHG crystal
- New Cavity-Mirrors for Lattice
Detection in Triplet-MOT:
• Background free
• Can’t be done while the lattice is turned on
  → Ionization by lattice photons

Solution: Transfer atoms to 1064 nm dipole trap after spectroscopy
• Detection of $^3P_0$ atoms in T-MOT
• Transfer of $^1S_0$ atoms to $^3P_1$ and second T-MOT phase

First proof-of-principal test have shown a nearly 100% transfer efficiency from the lattice back to the dipole trap for both states
Fermions are more favorable than Bosons for optical clocks

- Suppressed s-wave collisions
- Clock-Laser AC-Stark small due to low required intensities
- Zeeman-Effect can be characterized with interleaved $m_F$ measurements
  - Two times longer measurement reduces stability (Dick-Effect)

but

- Sensitive to lattice polarization (Tensor- & Vector-shift)
  - Can also be characterized with interleaved $m_F$ measurements

Hyper-Ramsey method promising to reduce shift due to probe-pulses
- Less Clock-Laser AC-Stark sensitivity. No B-Fields during free evolution time

Bosonic Magnesium Clock

- Density controlled: 1 atom every 12 lattice sites
- Future implementation of spectroscopy: Hyper-Ramsey scheme?
- Tunneling
- Normalization + Background free detection in T-MOT
Thank you