Sr optical lattice

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Michigan Quantum Summer School
Ann Arbor, June 16, 2008
# Alkaline Earth versus Alkali

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<thead>
<tr>
<th>Alkali</th>
<th>Alkaline Earth</th>
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<tr>
<td>All-Optical Cooling to Ultra-Low Temperatures</td>
<td>High Density</td>
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<td>Polarization Gradient</td>
<td>Intercombination line sub-recoil</td>
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<td>Stimulated Raman</td>
<td>Sideband Cooling in Dipole Traps</td>
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<td>VSCPT</td>
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<td>Feshbach Resonances</td>
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<td>Hyperfine structure</td>
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<td>Ground-State Magnetic Traps</td>
<td>Diversity of Bose, Fermi Isotopes</td>
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<td>Tunable Interactions</td>
<td>Optical Feshbach resonance</td>
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<tr>
<td>Only two Fermions: $^{40}$K, $^{6}$Li</td>
<td>Structure Free Ground State</td>
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<td>Time / Frequency Metrology</td>
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<td>Microwave Clocks</td>
<td>High Optical Line Q</td>
</tr>
<tr>
<td>Small Optical Line Q</td>
<td>Second-Stage Cooling Required</td>
</tr>
</tbody>
</table>
Strontium: Pre-cooling

- Large dipole moment
- Mostly closed transition
- J=0 to J=1
- Diode laser with frequency doubling

\[
\begin{align*}
\text{5s}^2 & \rightarrow 5s5p \\
1S_0 & \rightarrow 1P_1 \\
1P_1 & \rightarrow 1D_2 \\
3S_1 & \rightarrow 3P_J \\
3P_J & \rightarrow 3D_J
\end{align*}
\]
Strontium: Narrow Line Laser Cooling

- smaller dipole moment
- closed transition
- $J=0$ to $J=1$
- diode laser accessible
• HFI provides $^{1}S_{0}$-$^{3}P_{0}$ clock (~ 1mHz)
• field insensitive states
• diode laser
• accessible Stark-free confinement wavelength
• clock states $J=0$
Quantum Simulations with Alkaline Earth

New Features:
- Metastable optical states
- Clock transition – spectral resolution
- Nuclear spin decouples from the electronic state

Implementation:
- Nuclear spin states for quantum information storage
- Electronic state for:
  - Creation of state-dependent lattices
  - Access to control and readout
- Many ideas originally invented for Alkali atoms freed from technical problems
- New possibilities
State-dependent lattices

Dressed Potentials:
- Resonant coupling on clock transition
- Use a standing wave (oscillating Rabi frequency)
- AC-Stark split states:

Spin-dependent lattices:
- Differential Zeeman shift
- Frequency-addressed resonant coupling
- Separately controllable lattices for two nuclear spins

Andrew Daley and Peter Zoller
Optical atomic clocks

- Feedback (accuracy)
- Ultrastable laser
- Sr atoms
- Optical frequency synthesizer & counter
- Optical comb
- Readout: Comparison & distribution
Control of matter

Long- term quantum coherence:

Clean separation between internal & external degrees of freedom

Both in well defined quantum states
Cool Alkaline Earth – Strontium

JILA, SYRTE, Tokyo, LENS, PTB, NPL, NRC, NIM

How many cycles are there in the $^3P_0$ lifetime?

\[
(4.3 \times 10^{14} \text{ Hz}) \times (150 \text{ s}) = 6.5 \times 10^{16}
\]

or, in fractional terms: \(1.5 \times 10^{-17}\)

\[
\delta = -800 \text{ kHz}
\]

\[
\delta = -1800 \text{ kHz}
\]

\[
\delta = -2800 \text{ kHz}
\]
Quantum metrology in optical lattice

- Atomic confinement $\ll \lambda$ ($e^{ikx} \sim 1$, $k = 2\pi/\lambda_{\text{probe}}$)

- Trap potential identical for $^1S_0$ and $^3P_0$

Ye, Kimble, Katori, Science (June 27, 2008).

- $N$ quantum absorbers improve precision by $N^{1/2}$
- No ac Stark shift from the trap; Collision shift minimized
- Long observation time; Zero Doppler shift, Zero recoil shift
Sr energy levels

\[ 5snp^3P_1 \quad 5snp^3S_1 \quad 5p^{23}P_0,1,2 \quad 5s5d^3D_{1,2,3} \quad 5s5p^3P_{0,1,2} \quad 5s^21S_0 \]

\[ \lambda_{\text{trap}} \approx 460 \text{ nm} \]

\[ \lambda_{\text{trap}} \approx 490 \text{ nm} \]

\[ \lambda_{\text{trap}} \approx 480 \text{ nm} \]

\[ \lambda_{\text{trap}} \approx 680 \text{ nm} \]

\[ \lambda_{\text{trap}} \approx 2.7 \mu\text{m} \]
Crossing of polarizabilities

Ye, Kimble, & Katori, Science, June 27, 2008.
It's a mess if $J \neq 0$
Important Regimes for Spectroscopy

\[ \omega_{\text{trap}} \gg \Gamma \] well-resolved sideband

Lamb-Dicke

\[ \omega_{\text{trap}} \gg \omega_{\text{recoil}} \]

uniform confinement
Spectroscopy at the magic wavelength


Carrier: Doppler free
Recoil free

Photon counts

Optical frequency (kHz)

Clock probe
Zoom into the carrier of $^{87}\text{Sr} \ 1S_0 - 3P_0$

$Q \sim 1 \times 10^{14}$

- Single trace without averaging

$\text{FWHM: } 4.6 \text{ Hz}$

April, 2006

Magnetic Broadening

$^1S_0 - ^3P_0$ Linewidth (Hz) vs Magnetic Field (mG)
Differential $g$-factor & Tensor polarizability

$|^{3}P_{0}^{'}>=|^{3}P_{0}> +c_{1}|^{1}P_{1}> +c_{2}|^{3}P_{1}>

- $^{3}P_{0}$ $g$-factor different from $^{1}S_{0}$ due to hyperfine
- $m_{F}$ – dependent vector & tensor AC shifts from the lattice trap
- All can be determined with high-resolution measurement

Proposals & work based on Bosons:

Hong et al., PRL 94, 050801 (2005).
Barber et al., PRL 96, 083002 (2006).
Zanon et al., PRL 97, 233001 (2006).
Baillard et al., OL 32, 1812 (2007).
Optical Measurement of Nuclear $g$-factor


No net electronic angular momentum

$\Delta g = -108.4(4)$ Hz/(G m$_F$)

$^3P_0$ lifetime 140(40) s
Scalar, vector, tensor polarizabilities


\[ \begin{align*}
3P_0 & \quad -\frac{9}{2} - \frac{7}{2} - \frac{5}{2} - \frac{3}{2} - \frac{1}{2} + \frac{1}{2} + \frac{3}{2} + \frac{5}{2} + \frac{7}{2} + \frac{9}{2} \\
1S_0 & \quad -\frac{9}{2} - \frac{7}{2} - \frac{5}{2} - \frac{3}{2} - \frac{1}{2} + \frac{1}{2} + \frac{3}{2} + \frac{5}{2} + \frac{7}{2} + \frac{9}{2}
\end{align*} \]

\[ \nu_{\pi mF} = \nu_0 - \Delta g m_F \mu_0 B - (\Delta \alpha^S - \Delta \alpha^T F(F+1)) I_{trap} - (\Delta \alpha^V \xi m_F + \Delta \alpha^T 3m_F^2) I_{trap} \]

Hyperpolarizability
\[ \sim (I_{trap})^2 : <1E-17 \]

P. Lemonde, SYRTE

\[ \Delta \alpha : \text{differential polarizability} \]

\[ \xi : \text{polarization ellipticity} \]

Clock frequency

1\textsuperscript{st} order Zeeman

Scalar + Tensor polarizability

Vector + Tensor polarizability
Coherent spectroscopy $Q \sim 2.5 \times 10^{14}$


- Instability $\sim 2 \times 10^{-15}/\sqrt{\tau}$
- Inaccuracy $\sim 1 \times 10^{-16}$
Optical manipulation of nuclear spins

- Optically addressed, long coherence time
- Nuclear spin entanglement via electronic dipolar interactions
- Control electronic interaction via nuclear spins
- Cooling of atoms without nuclear spin decoherence (Deutsch)
- Individually addressable via a magnetic gradient field
Clock operation – Atom Lock & Normalization

Normalization
Reduction of atom number fluctuations

Lock to Atoms
Signal integration from both spin-polarized peaks

461nm

698 nm clock

$^{1}S_{0}$

$^{3}P_{0}$

$^{3}P_{1}$

$^{3}P_{2}$

$^{3}S_{1}$
Clock comparison: Sr lattice / Cs-fountain

Absolute freq. measurement: ±0.4 Hz (8.5×10^{-16})
(limited by Cs/H-maser)

Need better clocks
Annual variations?
Fundamental constants & gravitational potential

S. Blatt et al.,
Constraints on possible time-dependent variations of fundamental constants

Sr frequency drift < 4.6 x 10^{-16}/year

$\alpha$: fine-structure constant
$\mu$: electron/proton mass ratio

Ultracold molecules:

Test fundamental principles

One system, two different fundamental forces!

Excited electronic state

Ground electronic state

Electronic $\sim \alpha$

Vibration $\sim m_e/m_p$ (mass on a spring)

QED

Strong interactions
Strontium optical Feshbach resonance

- Narrow line
- Structureless ground state in $^{88}\text{Sr}$
Near threshold Photoassociation


$10^{-5}$ agreement between experiment and theory

Nine least bound states measured
Ultracold $\text{Sr}_2$ Molecules in Lattice

- Ground and excited state potentials similar – favorable decay to electronic ground state
- Structureless ground state

Raman transition for ground state production
Molecular Clock - Sensitivity to Mass Ratio


- Molecular potentials depend on electron mass, $m_e$
- Kinetic energy depends on proton mass, $m_p$
- Vibrational spacings depend on $m_p / m_e$

- Precision tests of time variation of $m_p / m_e$?

D. DeMille, PRL 100, 043202 (2008).
C. Chardonnet, SF$_6$

Sr$_2$ in lattice
Optical clock comparison - Sr vs. Ca

Ludlow et al. (JILA);
Fortier et al. (NIST)
Optical clock comparison – Sr vs. Ca

Ludlow et al. (JILA);
Fortier et al. (NIST)
Magic wavelength trap

Ye, Kimble, & Katori, Science, June 27, 2008.

0.08 (0.03) Hz
# Atomic Systematics


<table>
<thead>
<tr>
<th>Contributor</th>
<th>Correction ($10^{-16}$)</th>
<th>Uncertainty ($10^{-16}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Stark (scalar/tensor)</td>
<td>$-6.5$</td>
<td>$0.5$</td>
</tr>
<tr>
<td>Hyperpolarizability (lattice)</td>
<td>$-0.2$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>BBR Stark</td>
<td>$52.1$</td>
<td>$1.0$</td>
</tr>
<tr>
<td>ac Stark (probe)</td>
<td>$0.2$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>First-order Zeeman</td>
<td>$0.2$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>Second-order Zeeman</td>
<td>$0.2$</td>
<td>$0.02$</td>
</tr>
<tr>
<td>Density</td>
<td>$8.9$</td>
<td>$0.8$</td>
</tr>
<tr>
<td>Line pulling</td>
<td>$0$</td>
<td>$0.2$</td>
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<tr>
<td>Servo error</td>
<td>$0$</td>
<td>$0.5$</td>
</tr>
<tr>
<td>Second-order Doppler</td>
<td>$0$</td>
<td>$&lt;&lt;0.01$</td>
</tr>
<tr>
<td>Systematic total</td>
<td>$54.9$</td>
<td>$1.5$</td>
</tr>
</tbody>
</table>
Reading out atomic interactions via clock shifts

A. Ludlow et al., Science 319, 1805 (2008)

< 1 x 10^{-16} uncertainty

$\frac{1}{3} P_0$

$\frac{1}{1} S_0$

Density $3 \times 10^{11}$/cm$^3$
Decoherence inhomogeneity inside lattice

G. K. Campbell et al.

Smaller clock shift

Rabi probe

Excitation

Time [ms]

1 µK

3 µK
Blackbody Radiation Shift

current uncertainty: $1 \times 10^{-16}$

$$\delta E \approx -\frac{2}{15} (\alpha \pi)^3 T^4 \alpha_d(0)[1 + \eta]$$

Static Polarizability Measurements

- DC Electric Field
- Dynamic Polarizability
- Long $\lambda$ Stark measurement
- BBR controlled measurement

trapping and cooling

BBR chamber
Accurate atomic clocks
What is the noise?
Quantum projection measurement

Wineland et al., 1993; Polzik et al., 1998; Jessen et al., 2006

Spin squeezing via measurement of lattice
- in collaboration with D. Meiser & M. Holland
Special thanks

Ultracold Sr

M. Boyd
A. Ludlow
S. Blatt
G. Campbell
M. Martin

T. Zelevinsky (Columbia)
T. Zanon (Univ. Paris 13)
T. Ido (Tokyo)
T. Loftus (U. Washington)
J. Thomsen (Copenhagen)

M. Holland, C. Greene (JILA)
P. Julienne (NIST), S. Porsev (Petersburg), E. Arimondo (Pisa), P. Zoller