Rydberg Atoms as Sensors

Transmission vs. Probe Detuning (MHz)

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The University of Oklahoma, Atomic, Molecular and Optical Physics
Motivation

- Electrometry with Rydberg atoms: Rydberg atoms have narrow bandwidth, traceable MW detectors.
- Quantum assisted sensing: detecting MW fields through a coherent 3 photon process using each atom as an interferometer.
- Setup can also be used to investigate the four level system with Rydberg states as well as probe Rydberg interactions.

- Rydberg atoms are atoms with an excited electron.
  - Alkali atoms $n \sim 20 – 100$
- Rydberg states of alkalis resemble that of hydrogen.
  - Universal $n$ scaling laws
- High sensitivity to external perturbations

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Scaling</th>
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</thead>
<tbody>
<tr>
<td>Radius</td>
<td>$\langle r \rangle$</td>
<td>$n^2$</td>
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<tr>
<td>Transition Dipole</td>
<td>$\langle nl</td>
<td>er</td>
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<td>Polarizability</td>
<td>$\alpha$</td>
<td>$n^7$</td>
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<td>Dipole-Dipole Interaction</td>
<td>$C_6$</td>
<td>$n^{11}$</td>
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Precision Measurement and Atom-based Sensing

- Atomic Sensors
  - Atomic clocks – time/frequency
  - Magnetometers – B fields
  - Inertial force sensors

- Advantages
  - Linked to fundamental constants and properties of the atom
  - Stability, reproducibility
  - Miniaturization – atomic clock

- Self calibrated.
- Quantum interference and squeezing.
Dipole antenna is the current standard for microwave electric field measurement.

- Min. detectable field: \( \sim 70 \, \mu\text{V/cm} \)
- Sensitivity: \( \sim 1 \, \text{mV/cm Hz}^{-1/2} \)
- Accuracy: \( \sim 4-20\% \) (depending on frequency)

Limitations of dipole antennas

- Geometry - variation
- Theory of antennas
- Perturbation of the field
- Reproducibility, aging
- Size dependent – no antennas far infrared
- Usually exist in large laboratories - NIST
• Dark state (EIT) with 852 nm and 509 nm laser.

• Bright state with microwave (Autler-Townes splitting).

\[ \Omega_{MW} = \frac{E_{MW} \cdot \mu}{\hbar} \]

• Sensitivity to microwave is large because dipole moment is large.

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Sensitivity

- Example: Rubidium 55D to 54F transition
- $\Delta E = 14 \text{ GHz}$, within $K_u$ band
- 1 nW of microwave power in a 6” diameter
- Intensity of 5 fW/cm$^2$
- AC Field of only 64 $\mu$V/cm
- Rabi Frequency is 1 MHz!

Quantum Defects:

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<th>n</th>
<th>l</th>
<th>j</th>
<th>n'</th>
<th>l'</th>
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Experimental Setup

- $^{87}\text{Rb}$ or $^{133}\text{Cs}$ in a vapor cell
- $780\text{nm}$ ($^{87}\text{Rb}$) or $852\text{nm}$ ($^{133}\text{Cs}$) probe diode laser
- $480\text{nm}$ ($^{87}\text{Rb}$) or $509\text{nm}$ ($^{133}\text{Cs}$) frequency doubled in a bowtie cavity
- Optical readout
- Portable
Autler-Townes Splitting

- In Autler-Townes regime, peaks split by:
  \[ \frac{\Omega_{RF} \frac{\lambda_c}{\lambda_p}}{2\pi} \]

- Traceable – peak splitting depends on dipole moment of transition and transition wavelengths

\[ \Omega = \frac{E \cdot \mu}{\hbar} \]
• In Autler-Townes regime peaks split by:

\[ \nu_{sp} = \frac{\Omega_{mw} \lambda_c}{2\pi \lambda_p} \]

• Calculate the electric field:

\[ E_{mw} = \frac{2\pi \hbar \nu_{sp} \lambda_p}{\mu \lambda_c} \]

• Splitting uncertainty < 0.5%

• Dipole moment uncertainty ~1%

\[ \langle R_{n'l'}(r) | e r | R_{nl}(r) \rangle_{5S_{1/2} \leftrightarrow 5P_{3/2}} = 5.178 e \, a_0 \]

\[ \langle R_{n'l'}(r) | e r | R_{nl}(r) \rangle_{5P_{3/2} \leftrightarrow 53D_{5/2}} = 2.394 \times 10^{-2} e \, a_0 \]

\[ \langle R_{n'l'}(r) | e r | R_{nl}(r) \rangle_{53D_{5/2} \leftrightarrow 54P_{3/2}} = 3611 e \, a_0 \]
In the Autler-Townes regime the splitting can be predicted accurately using a 4-level theory. Other changes in the lineshape require taking all the levels involved in the EIT into account.
Frequency Modulation Spectroscopy

(a) 55 \mu V/cm
   - 7 \mu V/cm
   - 27.5 \mu V/cm
   - 3.5 \mu V/cm
   - 14 \mu V/cm
   - 1.8 \mu V/cm

(b) 55 \mu V/cm
   - 7 \mu V/cm
   - 27.5 \mu V/cm
   - 3.5 \mu V/cm
   - 14 \mu V/cm
   - 1.8 \mu V/cm

Probe Transmission (a.u.) vs. RF detuning (MHz)
Low MW Fields-Sensitivity

- Lowest detected field is \( \sim 1 \, \mu\text{V cm}^{-1} \)
- The sensitivity \( \sim 3 \, \mu\text{V cm}^{-1}\text{Hz}^{-1/2} \)
- Current traceable standards:
  - 70 \( \mu\text{V cm}^{-1} \) (minimum detectable field)
  - 1 \( \text{mV cm}^{-1}\text{Hz}^{-1/2} \) (sensitivity)

\[ \text{Probe Transmission (a.u.)} \]

\[ \text{\( \Delta_{\text{MW}} \) (MHz)} \]

\[ \begin{align*}
&83.3 \, \mu\text{V/cm} \\
&74.2 \, \mu\text{V/cm} \\
&66.2 \, \mu\text{V/cm} \\
&59.0 \, \mu\text{V/cm} \\
&46.8 \, \mu\text{V/cm} \\
&37.2 \, \mu\text{V/cm} \\
&29.5 \, \mu\text{V/cm} \\
&18.6 \, \mu\text{V/cm} \\
&8.33 \, \mu\text{V/cm} \\
\end{align*} \]

\[ \text{% Increase in Transmission} \]

\[ \text{Efield (\mu V/cm)} \]

- J. A. Sedlacek, et. al, Nat. Phys. 8, 11 (2012)
Transition Dipole Moment

- Large transition dipole moment
- Possible high sensitivity – shot noise limit
- Large frequency range: GHz~THz
Antenna Experiment Setup

- \( \lambda = 4.3 \text{ cm.} \)
- 852 nm and 509 nm counter propagate.
- Imaging system: CCD + lens.
- Horn and Al plate form a standing wave.
- Microwave shielding.
- 3D Helmholtz coil to cancel residual magnetic field.

\[ \text{47D}_{5/2} \rightarrow \text{509 nm} \quad \Omega_c \]
\[ \text{6P}_{3/2} \rightarrow \text{852 nm} \quad \Omega_p \]
\[ \text{48P}_{3/2} \rightarrow \text{6S}_{1/2} \quad \text{MW} 6.9 \text{ GHz} \]
Subwavelength E-field imaging

- Image of the probe profile
- Intensity of each pixel at different detunings
- Aulter-Townes splitting – E-field amplitude
- Intensity of laser beam – E-field distribution
Image Measurement

The spatial resolution is \( \sim 66 \, \mu\text{m} \) which is \( \sim \lambda/650 \) with field resolution at \( \sim 30 \, \mu\text{V/cm} \).
Near Field Imaging

- Coplanar waveguide (CPW)
- Spatial resolution
- Electric field pattern
Near Field Imaging

- Image data and finite element simulation.
- Fit with near field microwave pattern $A \exp(-2\pi z/\lambda)$.
- Spatial resolution is the same.
De-phasing

- Under shot noise limit, the sensitivity is determined by the dephasing time \( T_2 \)

\[
\frac{E_{\text{min}}}{\sqrt{Hz}} = \frac{h}{\mu \sqrt{N_{\text{at}} T_2}}
\]

- Number of atoms: \( N_{\text{at}} \)

- Transition dipole moment: \( \mu \)

- Primary effects influencing \( T_2 \)
  - Collisions
  - Transit time broadening
Subwavelength E-field Imaging

Antenna Design
Eliminate the presence of conducting material near the sample, minimizing the field disturbance.

High Frequency Circuit Design
Near field measurement of metamaterials, antennas, etc.
Applications

Candidate for standard antenna

- The high sensitivity achieved, high accuracy
- Portable
- Self-calibrated
- Large frequency range GHz - THz

Conventional Antenna:

- Made of metal
- Disturb the target field
- Near field
- Antenna size – no subwavelength measurement
Conclusion

Min. traceable field: $\sim 70 \, \mu \text{V cm}^{-1}$
Sensitivity: $\sim 1 \, \text{mV cm}^{-1} \, \text{Hz}^{-1/2}$
Accuracy: $\sim 4\text{-}20\%$ (depending on frequency)

Min. traceable field: $\sim 1.00 \, \mu \text{V cm}^{-1}$.
Sensitivity: $\sim 3 \, \mu \text{V cm}^{-1} \, \text{Hz}^{-1/2}$.
Accuracy: $\sim 1\%$.
The spatial resolution: $\sim \lambda_{\text{mw}}/650$
Near Field measurement
Absolute measurement
Even higher sensitivity
Portable
Surface Interactions with Atoms, Ions, and Electrons

- Studying Fundamental Physics
  - Casimir-Polder force
  - Van der Waals force
  - Surface plasmon polaritons
  - Surface phonon polaritons

- Applications
  - Single photon subtraction
  - Quantum computation
    - Ion traps
    - Electrons on liquid helium
  - Creating hybrid systems.
  - Adsorbate fields can cause problems for these experiments.

H. Kübler et al., PRA 88, 043810 (2013)
J. Sheng et al., PRL, 117, 103201 (2016)
Rydberg Atoms – Hybrid Quantum Systems

- Interfacing Rydberg atoms with coplanar waveguides.
- Coupling Rydberg atoms to mechanical resonators.

J. D. Pritchard et al. PRA. 89 010301(R), 2014

- Hybrid Quantum gate

F. Bariani et al. PRA. 89 011801(R), 2014

- Quantum memory

M. Gao et al. PRA. 83 022309, 2011

D. Petrosyan et al. PRA. 79 04304(R), 2009

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Rydberg Atoms and Surface Phonon Polaritons

- Couple Rydberg atoms to SPhPs.
- Quantum nonlinear optics
  - Single photon subtraction
- Flying qubits
- Engineer surface polariton frequencies.

H. Kübler, D. Booth, J. Sedlacek, P. Zabawa, and J. P. Shaffer, PRA 88, 043810 (2013)

Y. Chao, J. Sheng, J. A. Sedlacek, and J. P. Shaffer, PRB 93, 045419 (2016)

J. Sheng, Y. Chao and J.P. Shaffer, PRL, 117, 103201 (2016)

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Rb Adsorbates

- Adsorbates are atoms or molecules bound to a surface.
  - Small dipole moment.
- Adsorbates can be due to background or trapped atoms.
- Can create large electric fields and gradients.
- Problematic for Rydberg atom experiments.
  - Polarizability $\sim n^7$
- Knowledge and control of these fields are needed for atom surface experiments.

D. A. Hite et al. PRL 109 103001, 2012
Experimental Apparatus

- Load ~ $1 \times 10^6$ $^{87}$Rb atoms in a Ioffe- Pritchard magnetic trap.
- Move atoms next to substrate.
- 500 μm thick z-cut (0001) single crystal quartz. Surface roughness < 5 angstroms.

(0001) Quartz Substrate

Gold Mirror

Copper Z Wire

Aluminum Nitride Mount
Rydberg EIT Near a Quartz Surface

- Rydberg EIT with absorption imaging
  - Counter-propagating probe and coupling beams.
  - Focused coupling beam creates a small transparent region in the atom cloud.
- Obtain spatial dependence of the electric field.
Detecting Adsorbates with Rydberg EIT

- An electric field shifts and broadens the EIT peak.
- Scanning the coupling (480 nm laser).

Stark splitting $81 D_{5/2}$

$B = 14.3 \text{ G}$

$z = 150 \text{ \mu m}$

$z = 50 \text{ \mu m}$

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Experimental Results

- Steady state fields
- Heating the substrate reduces the adsorbates on the quartz surface.

\[ \text{Electric Field (V/cm)} \]

Distance to quartz surface (μm)

\[ \text{T = 27 °C} \]

\[ \text{T = 38 °C} \]

\[ 75 \text{ D}_{5/2} \]

\[ 81 \text{ D}_{5/2} \]

\[ \text{Experiment (T = 27 °C)} \]

\[ \text{Experiment (T = 38 °C)} \]

\[ \text{Theoretical Fit} \]

\[ \text{Experiment (T = 48 °C)} \]

\[ \text{Experiment (T = 27 °C)} \]

\[ \text{Theoretical Fit} \]

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• In quartz, surface polariton near field ~ 20 µm.
  • Rydberg states ~ n = 37 – 100
  • 43S Stark shift < 20 kHz

Electric field < 50 mV/cm
Adsorbate Electric Fields

Electric field is homogeneous.
- Patch size $\sim L = 10 \text{ mm}$
- With 12 Debye per adatom
  - $\sim 4.2 \times 10^5 \text{ atoms}/\mu\text{m}^2$
- Langmuir isobar:

$$E_z(z) = \frac{2\sqrt{2}\sigma d(\sigma)L^2}{\pi\epsilon_0\sqrt{L^2 + 2z^2(L^2 + 4z^2)}}$$

$z = 500 \mu\text{m}$

$E_a = 0.66 \pm 0.02 \text{ eV}$
Neutralizing Adsorbate Field

- Creating Rydberg atoms in the MOT or Z trap reduces the adsorbate field.

- Similar to electrons bound in a 2D gas on the surface of liquid helium.
  - Electron is bound to image potential.
  - Rb adsorbate layer important for electron attachment.

\[ E_{\text{tot}} = E_{\text{ads}} + E_{\text{ele}} \]
Surface Electrons

- Similar to electrons bound in a 2D gas on the surface of liquid helium.
  - Electron can be bound in its image potential.
- Cold cathodes
- Rb adsorbate layer important for electron attachment.

Electrons will only be bound, if the surface has a negative electron affinity (NEA).

\[ \chi = E_{\text{vac}} - E_{\text{boc}} \]

Quartz has \( \chi = +0.9 \) eV.

Rubidium adsorbate dipole layer shifts the vacuum energy:

\[ \Delta \chi = -\frac{ed_0\sigma}{\epsilon_0(1 + 9\alpha_{\text{ad}}\sigma^{3/2})} = -1.9 \text{ eV} \]

Similar to adsorption of Cs on diamond and gallium nitride.

EIT near Quartz Surface

In the limit of high Rydberg atom population and $T = 79 \, ^\circ$C.

- At 20 µm, the electric field is 30 mV/cm.
- For distances > 200 µm the electric field is ≤ 5 mV/cm.

Recent experiments with Rb adsorbates

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<th>Electric Field (V/cm)</th>
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<td>0.5</td>
<td>100</td>
<td>Carter et al., PRA 86, 053401 (2012)</td>
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<td></td>
<td>8</td>
<td>20</td>
<td>Tauschinsky et al., PRA 81, 063411 (2010)</td>
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<td>Gold (w/ rubidium mirror)</td>
<td>0.1</td>
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<td>Hermann-Avigliano et al., PRA 90, 040502(R) (2014)</td>
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<td>Copper</td>
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<td>30</td>
<td>Hattermann et al., PRA 86, 022511 (2012)</td>
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<td>Titanium</td>
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<td>McGuirk et al., PRA 69, 062905 (2004)</td>
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