Terahertz (THz) and Radio-Frequency Sensing using Caesium Rydberg Atoms

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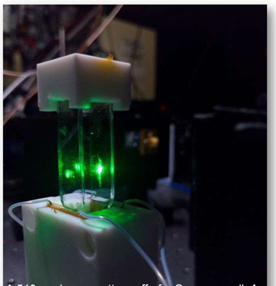
Abstract

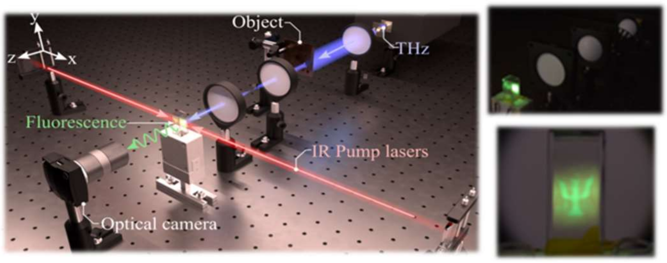
Rydberg atoms, those where the electron is excited to very high principal quantum numbers, have exaggerated properties that make them excellent **quantum sensors.** Using a caesium (Cs) Rydberg-atom receiver, we present simultaneous detection of radio-frequency (RF) fields ranging from the **very high-frequency** (VHF) band (128 MHz) to **terahertz frequencies** (0.61 THz) using states with **high orbital angular momentum**. Moreover, the experimental method presented allows for **high-resolution spectroscopy** of these states. We also outline our **THz full-field imager** using hot Rydberg atoms as THz-to-optical converters.



A 519 nm laser scatters off of a Cs vapor cell. An EHF microwave antenna (right) and THz horn (background) can be seen.

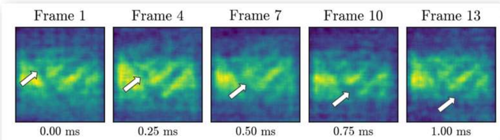
THz Fluorescence Imaging

THz imaging is useful for non-destructive testing (NDT) and medical diagnosis as an alternative to X-rays. We employ **Cs Rydberg atoms as THz-to-optical photon converters**[1,2] to provide full field images at many thousands of frames per second[3], that can be captured with conventional optical cameras.



The primary mechanism that enables this is the introduction of **a strong visible decay pathway** when the atoms are **coupled with a THz field**.

12,000 fps THz video!



Simultaneous Multiband rf Detection

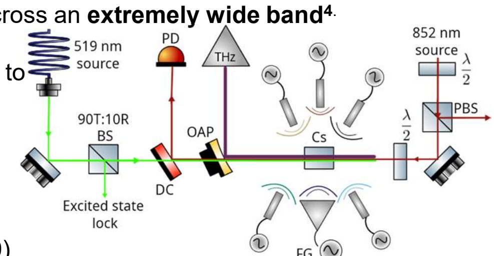
By using states with **high angular momentum**, ℓ, transition frequencies between low-lying Rydberg states can reach **radio frequencies (rf)** (VHF band). Applying **several fields** to couple many different states in a long chain allows detection of rf across an **extremely wide band**[4].

An infra-red 852 nm laser allows a **519 nm** optical laser to **couple nD** Rydberg states to the atomic ground state.

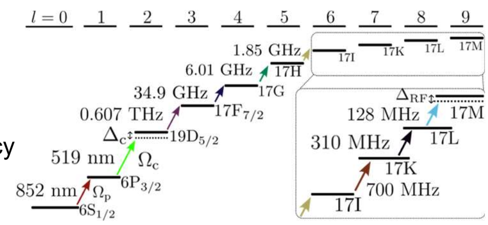
A **THz beam**, a series of horn and whip antennas spanning many octaves of rf, then couple to the 17M (ℓ = 9) state.

This allows detection across several discrete transitions from ***128 MHz to 0.607 THz.***

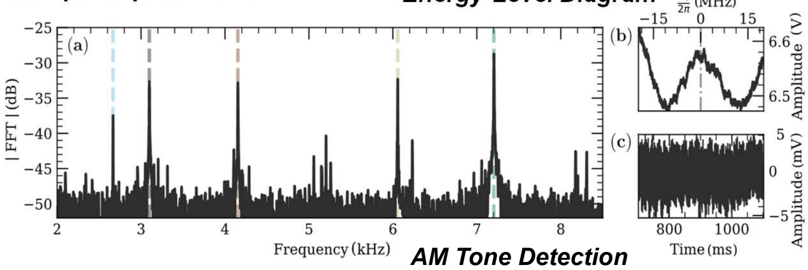
Amplitude modulation across each 'carrier' frequency can then be **independently detected** and mapped onto the **optical probe** laser.



Experimental Layout



Energy-Level Diagram



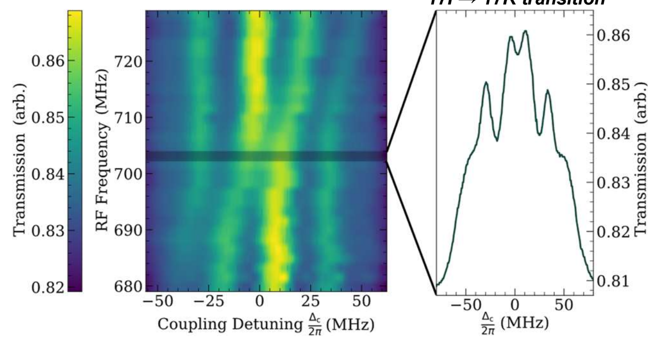
AM Tone Detection

High ℓ Spectroscopy

Rydberg electromagnetic induced transparency **(EIT)** allows non-destructive readout of the Cs atoms.

By examining detuning of Autler-Townes doublets, we can measure transition frequencies between neighboring states and determine **quantum defects**[5].

Spectral map of the 17I → 17K transition



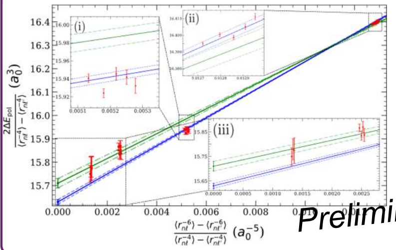
$$E_{n\ell j} = E_{I_{Cs}} - \frac{R_{Cs}}{(n - \delta_{\ell j}(n))^2}$$

$$\Delta E_{pol} = -\frac{1}{2}\alpha'_d \langle r_{n\ell}^{-4} \rangle - \frac{1}{2}\alpha'_q \langle r_{n\ell}^{-6} \rangle$$

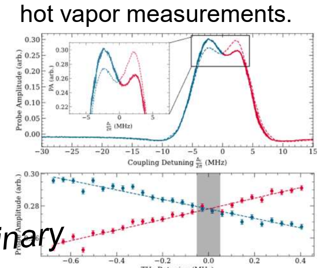
Spectroscopy of high angular momentum states can reveal information about the properties of the **Cs+ ionic core** and its interaction with the Rydberg electron.

Future Work and Outlook

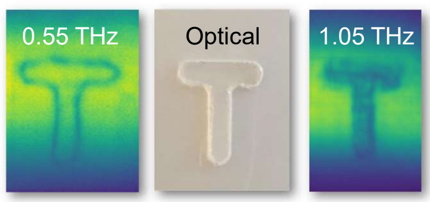
Core polarisability analysis of Cs, using measurements of high-angular-momentum states.



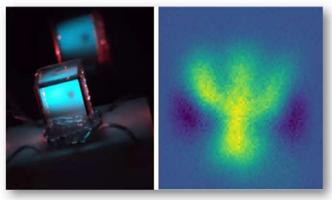
New quantum defect measurements in Cs using hot vapor measurements.



THz for **material discrimination** – shown is a Nylon 'T' embedded into a sheet of polypropylene at **different THz frequencies** giving **spectral information**.



Access different THz frequency transitions in different alkali metals, i.e. Rb, simultaneously. Leading to **multi-colour imaging.**



[1] - C. G. Wade et al., Nature Photonics 72, 40 (2017).
[2] - L. A. Downes, et al. Physical Review X 10.1 (2020): 011027.
[3] - L. A. Downes, et al. New Journal of Physics 25.3 (2023): 035002.
[4] - G. Allinson., et al. Physical Review Research (2024) (in press.)
[5] - G. Allinson., et al. (in preparation.)

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