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Microwave Spectroscopy of Ultracold Molecular Plasma

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Abstract

In this project, microwave radiation is used as a direct and selective tool to study Rydberg populations – states in which electrons have been excited to a very high principal quantum number – and plasma formation. In a custom-built vacuum chamber, a molecular beam composed of nitric oxide in a rare gas carrier is directed past a laser-interaction region to a distant micro-channel plate detector that is sensitive to charged particles. Nitric oxide molecules undergo a two-photon, resonant excitation to yield a cold, dense cloud of Rydberg molecules, which evolve into stable ultracold plasma. Resonant microwave fields allow the signal corresponding to different quantum numbers to be selectively enhanced in both the pulsed-field ionization (PFI) and the action spectrum of plasma. We demonstrate that two frequencies are resonant to each optically bright Rydberg state, and that they correspond to the energy spacing between adjacent quantum numbers, n. Microwave fields appear to substantially enhance the lifetime of excited molecules that exhibit rapid dissociation in field-free conditions. Finally, the results are compared to the microwave field effect in the presence of small dc electric fields, which, depending on the magnitude, either intensify or dramatically diminish the observed enhancements.

Plasma Formation

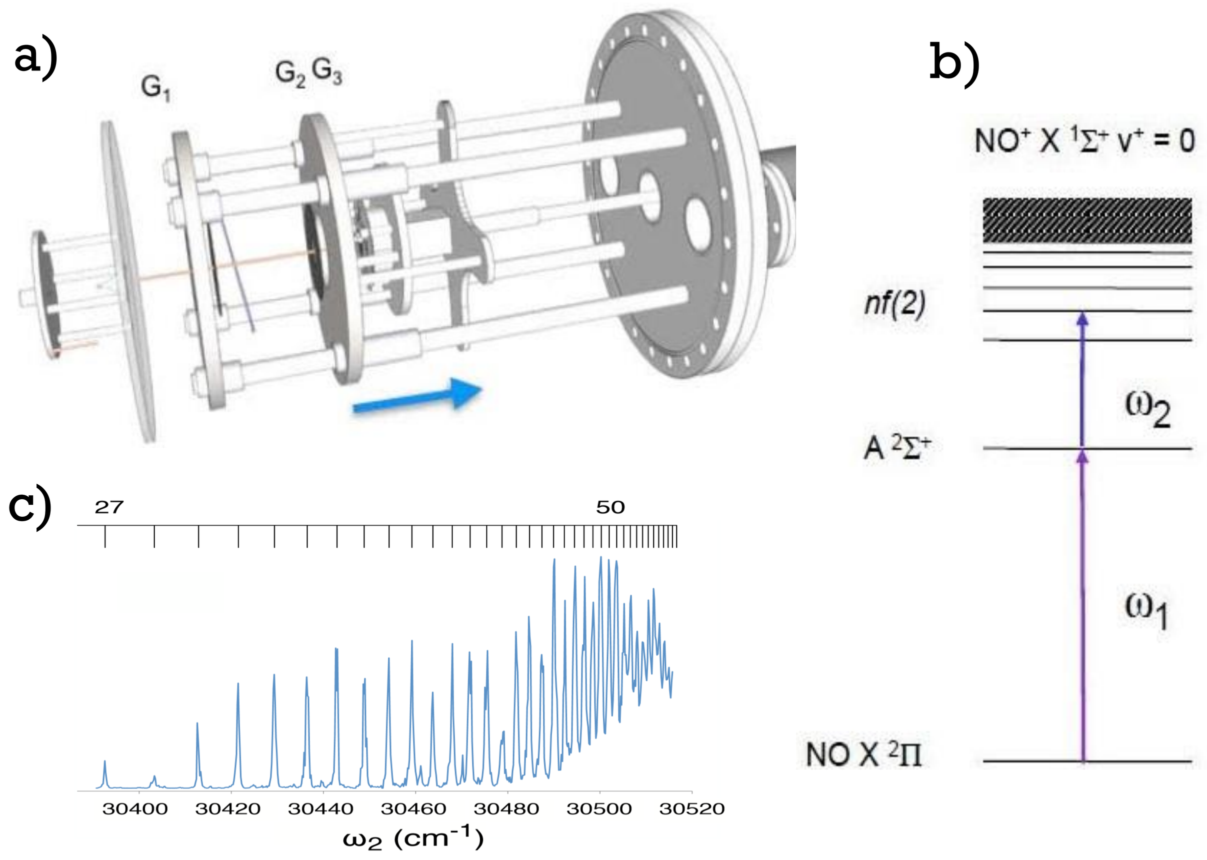

Figure 1. (a) A beam of nitric oxide (NO) is directed into a vacuum chamber. (b) A Nd:YAG pumped dye laser pulse (ω_1) excites a ground state NO to the excited A state. A second dye laser pulse (ω_2) creates a very cold (<1 K) Rydberg gas. (c) The Rydberg states evolve into stable ultracold plasma, which is observed in an action spectrum.

Experiment

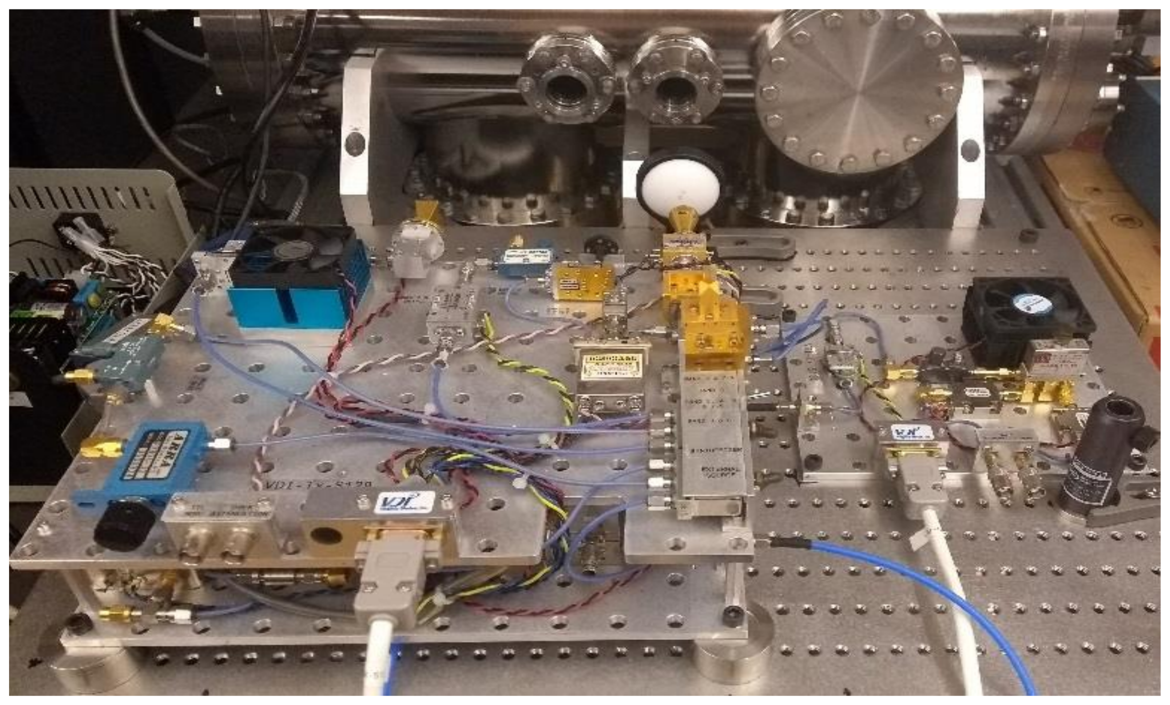

Figure 2. Gigahertz frequencies are applied with a controllable microwave generator. At resonant frequencies, significant enhancement of Rydberg populations is observed.

Signal Enhancement

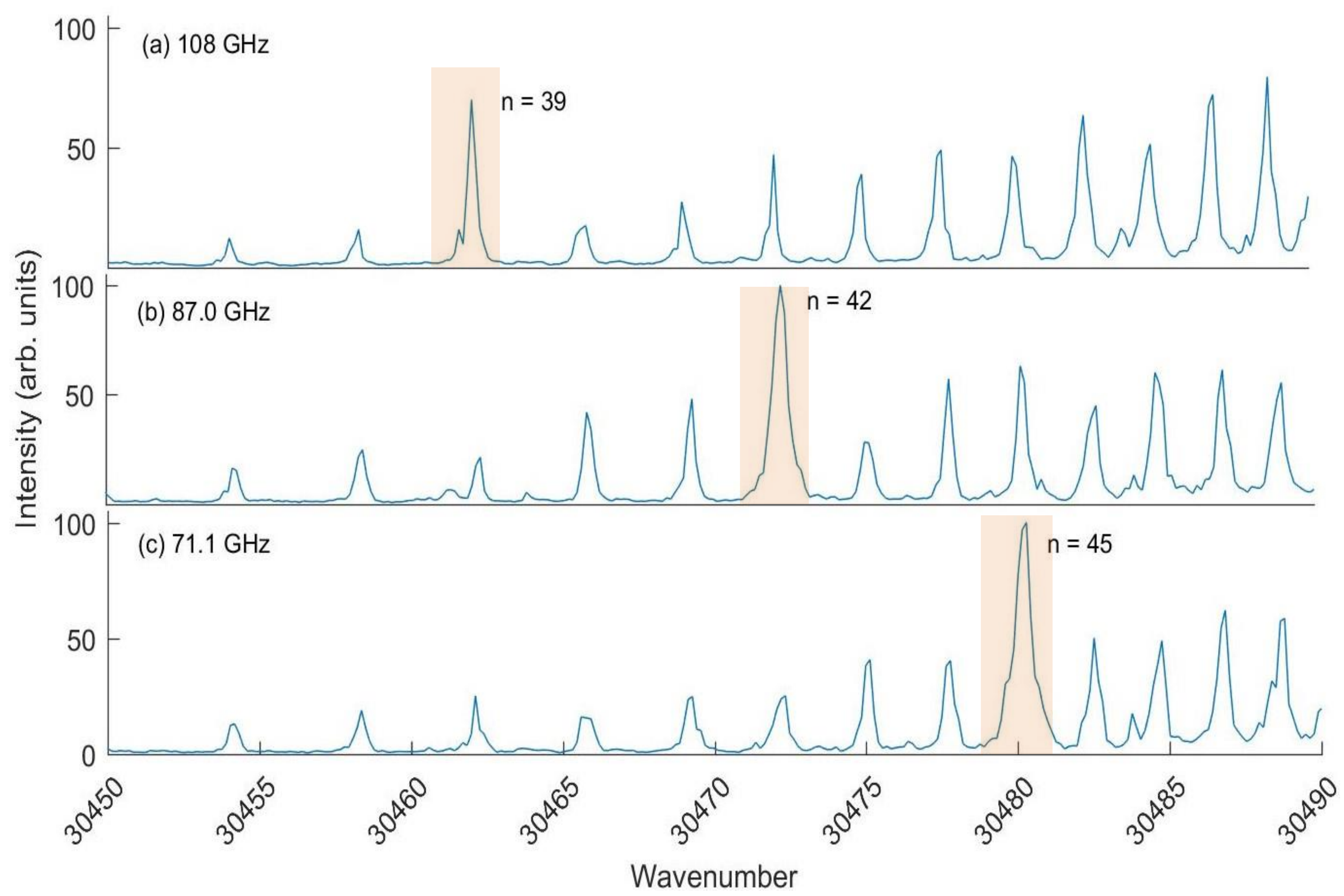

Figure 3. PFI spectra of NO at 0 V dc field and a constant microwave field of (a) 108 GHz, (b) 87.0 GHz and (c) 71.1 GHz.

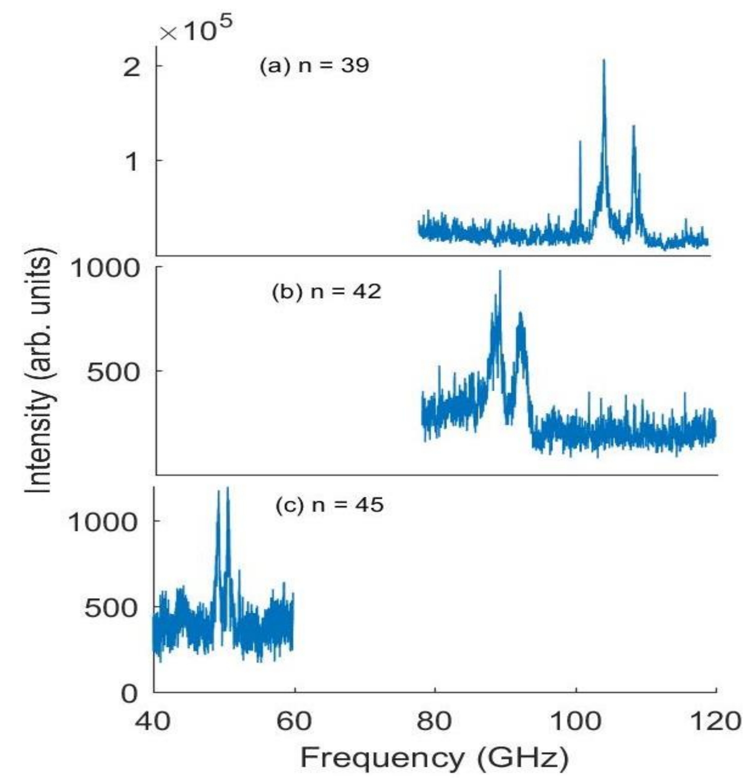

Figure 4. Frequency scans of NO at 0 V dc field at (a) n= 39*f*, (b) = 42*f* and (c) = 45*f*. Note: n = 39 is resonant to states with n = 38 and n = 40.

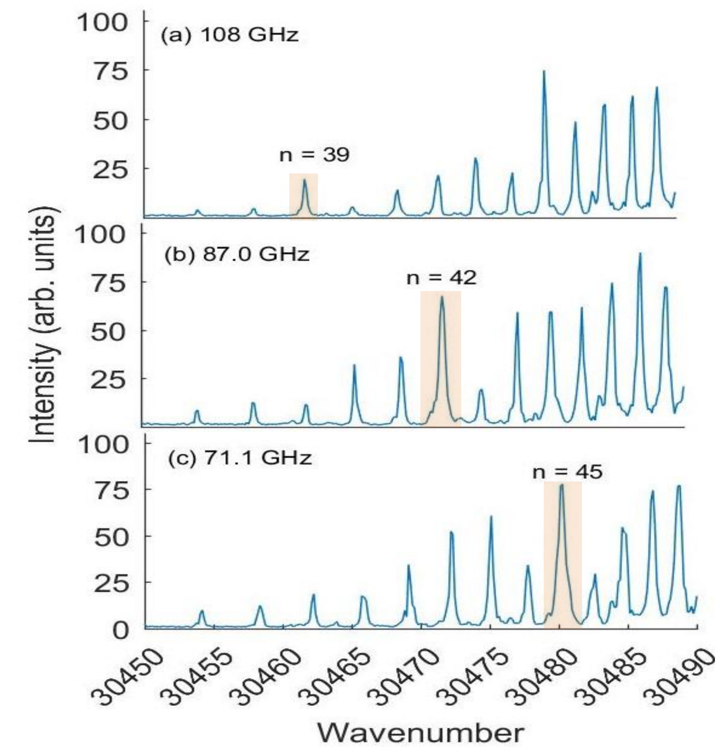

Figure 5. Plasma action spectra of NO at 0 V dc field and a constant microwave field of (a) 108, (b) 87.0 and (c) 71.1 GHz.

Pulsed Field Ionization Peak

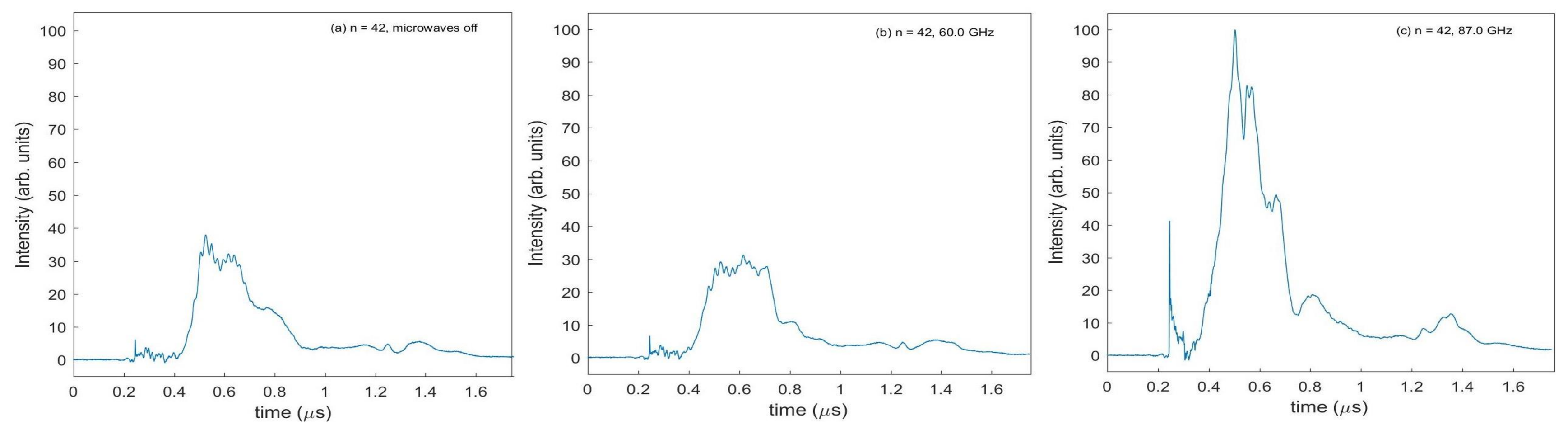

Figure 6. PFI peaks at n = 42*f* with 0 V dc field: (a) without microwaves; (b) with a non-resonant field of 60.0 GHz; and (c) with a resonant microwave field of 87.0 GHz.

A short lived species

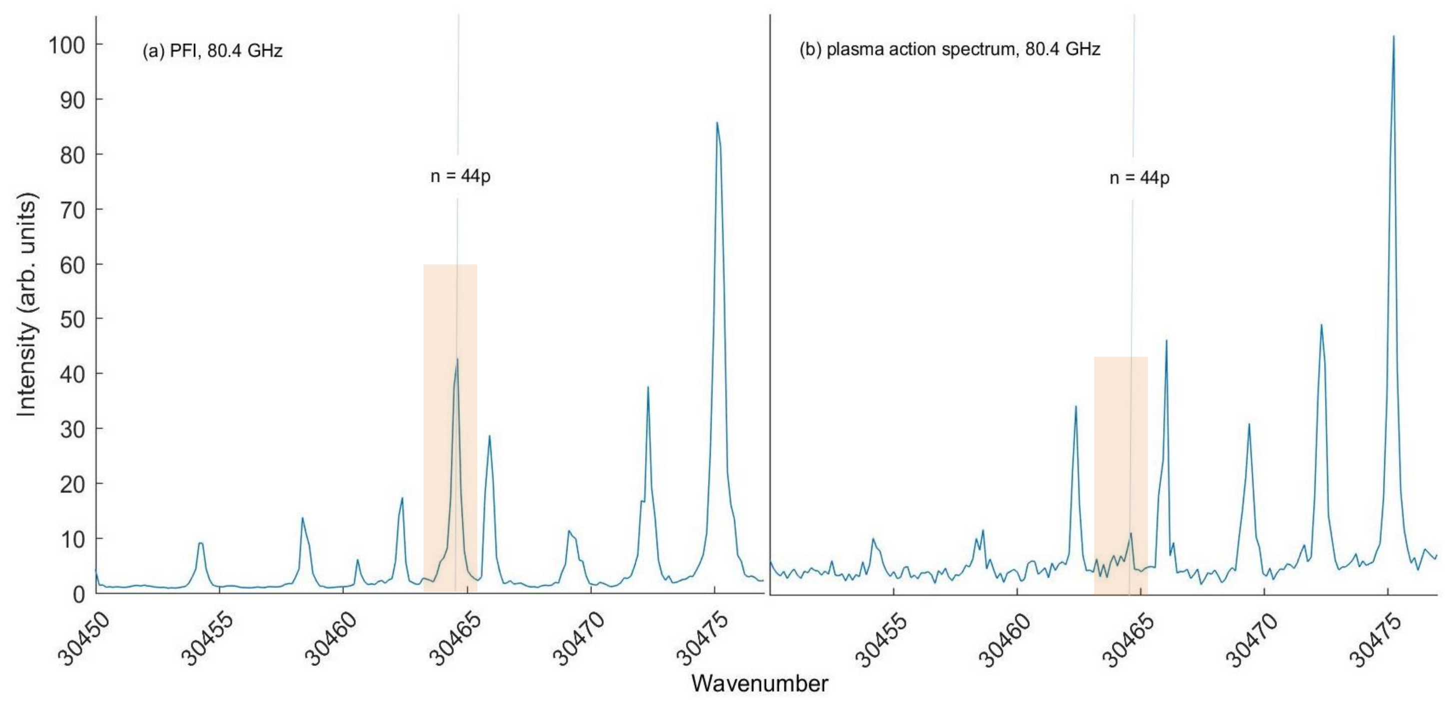

Figure 7. (a) PFI and (b) plasma action spectra of NO at a constant microwave field of 80.4 GHz. The PFI displays a signal for 44*p*, a species whose lifetime is too short to be detected without the resonant microwave field. Unlike the more dominant *f*-series, there is no enhancement on the action spectrum of the plasma peak.

Resonant Frequencies

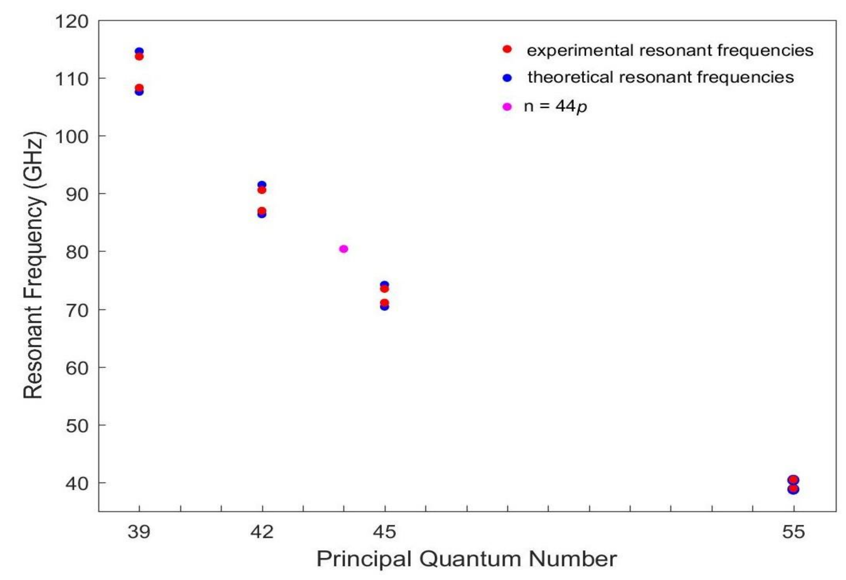

Figure 8. Resonant frequencies for n = 39, 42, 44*p*, 45 and 55.

Electric Field

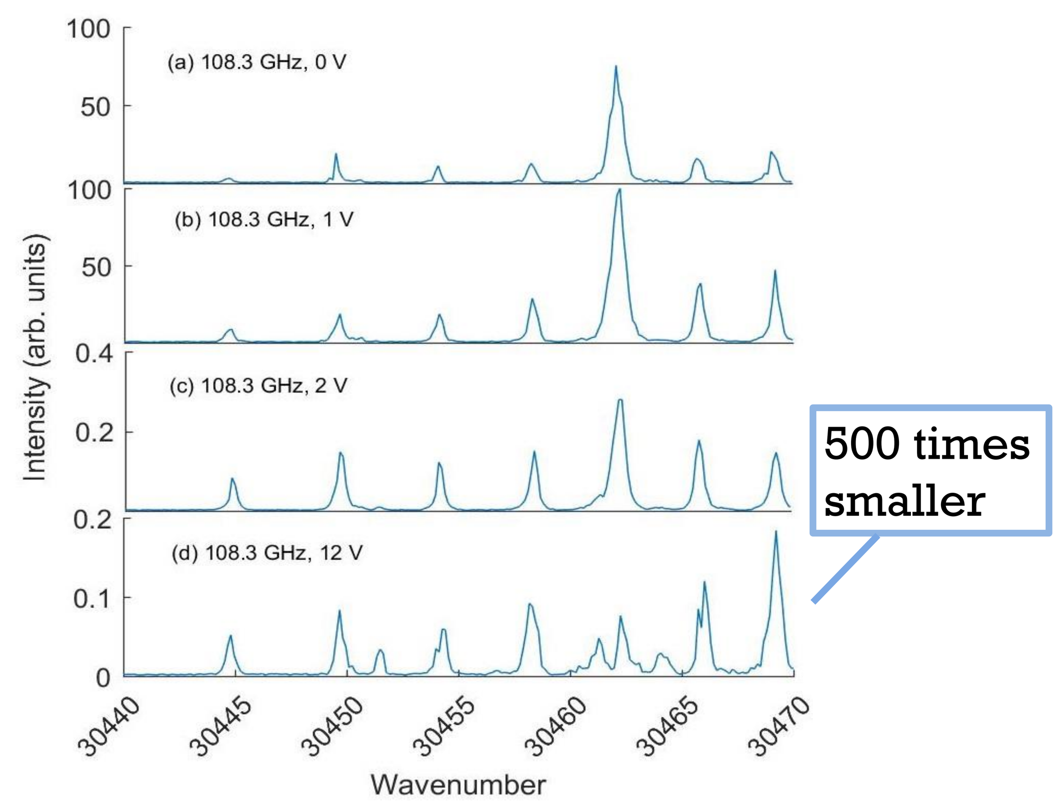

Figure 9. PFI spectra of NO at a constant microwave field of 108.3 GHz and (a) no dc field, and dc field of (b) 1 V, (c) 2 V and (d) 12 V.

Conclusions

- Two frequencies are resonant to each optically bright state. They correspond to the energy spacing between adjacent quantum numbers.
- Microwave field enhances the lifetime of excited molecules that would otherwise dissociate rapidly in field-free conditions.
- A small dc electric field enhances the PFI signal, but a larger field causes the signal to collapse.
- Microwave frequencies affect the lifetime of Rydberg states, and also plasma formation.

Future directions

What is the effect of microwave fields on plasma species with very short lifetime? Is microwave field a probe of quantum number dependent properties of plasma?

References

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Acknowledgements

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