Toward Measurements With Sympathetically Cooled State-Selected Molecular Ions

Ryan A. Carollo, David A. Lane, Alexander Frenett, David Hanneke
Department of Physics & Astronomy, Amherst College, Amherst, MA 01002

Quantum logic spectroscopy

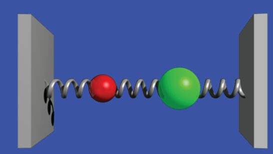
Leveraging quantum information processing techniques for precision measurement

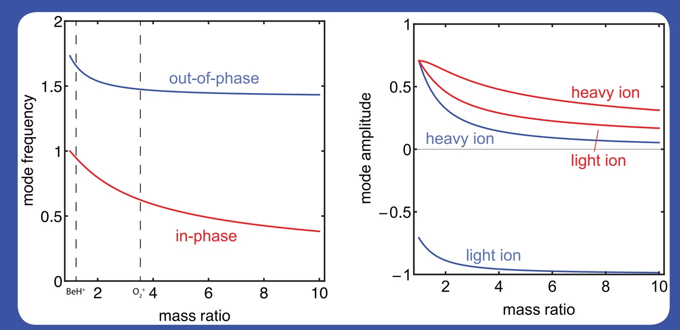
Atomic logic ion provides all dissipation
Target ion has an interesting spectroscopic transition

General procedure
- Co-trap ions
- External state preparation (sympathetic cooling)
- Internal state preparation (quantum projection)
- Spectroscopy probe of target ion
- State detection (non-destructive)

Our interest: molecules
- Quantum control of rotation states
- Rotation spectroscopy
- Quantum memory
- Tests of molecular quantum theory
- Time variation of fundamental constants
- Symmetry tests (P, T)

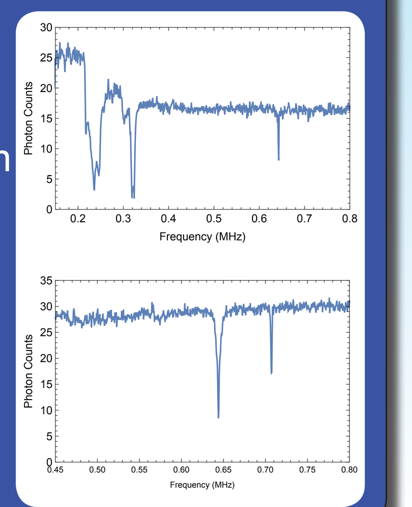
Normal modes:
an information bus shared by both ions





Detecting Normal Modes:

We measure our normal modes by resonant modulation of the trap potential through a DC electrode and detecting fluorescence with a PMT



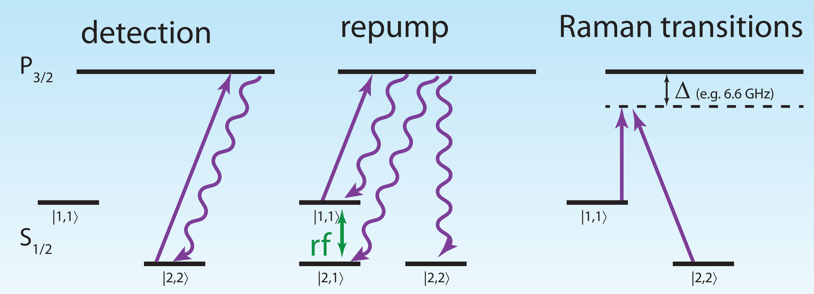
Deeply bound diatomic molecular ions are of interest for a variety of studies, such as precision measurements, quantum control of rotational states, or quantum memory. We are particularly interested in homonuclear systems, which show promise at suppressing certain systematic effects. We present an apparatus capable of controllably leaking O_2, ionizing and sympathetically cooling trapped O_2^+, and performing state-selective photoionization. We report on progress toward initial measurements with oxygen, and discuss a proposed precision measurement of the time variation of the proton-to-electron mass ratio using trapped O_2^+.

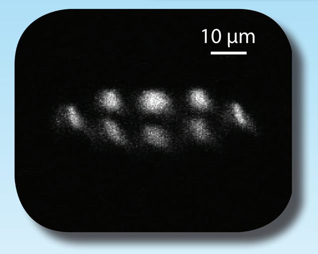
Beryllium logic ion

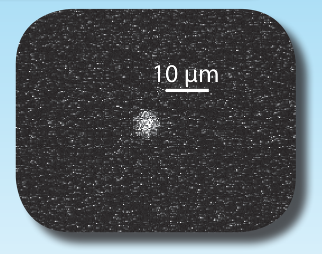
- Dissipation via photon scattering
- Hyperfine qubit
- Single isotope
- Ideal for lighter target ions

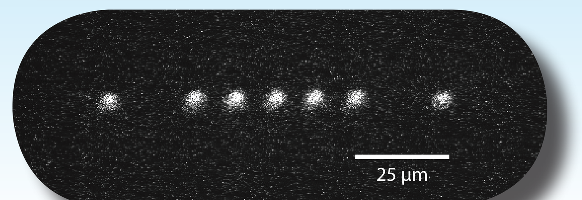
^{9}Be$^+$

$$I = 3/2$$
$$\Gamma = 2\pi(19.4\ \mathrm{MHz})$$
$$\nu_{\mathrm{hfs}} = 1.25\ \mathrm{GHz}$$





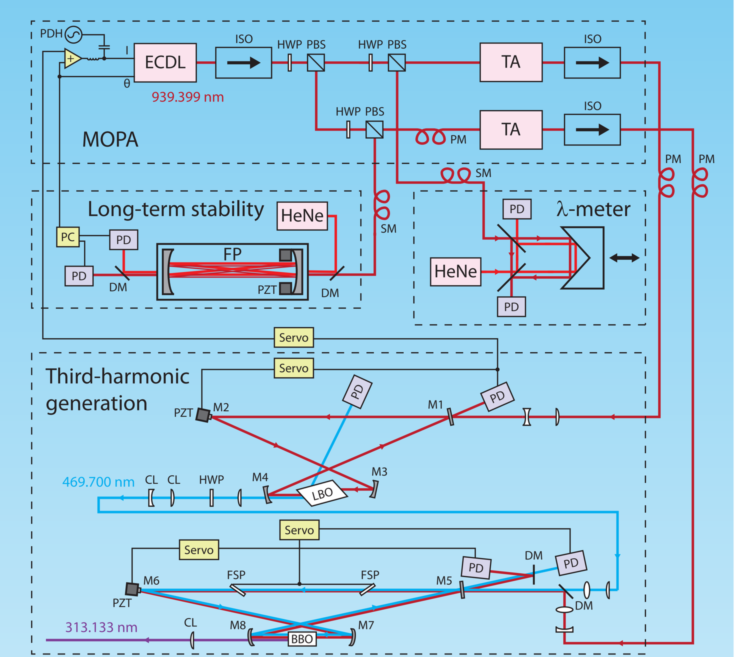


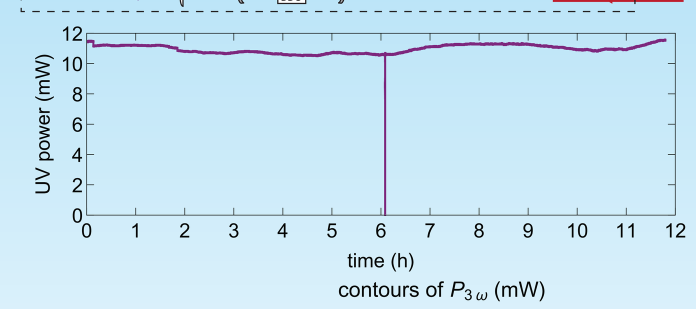


313 nm Be⁺ Laser

Lasers

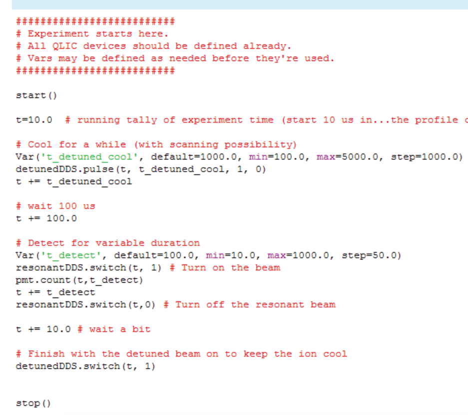
- Triple 939 nm diode laser to 313 nm (second-harmonic generation followed by sum-frequency generation)
- Up to 36 mW of power at 313 nm
- 10% power stability over 12 hours
- 3% short-term stability
- *Optics Express* **25**, 7220 (2017)

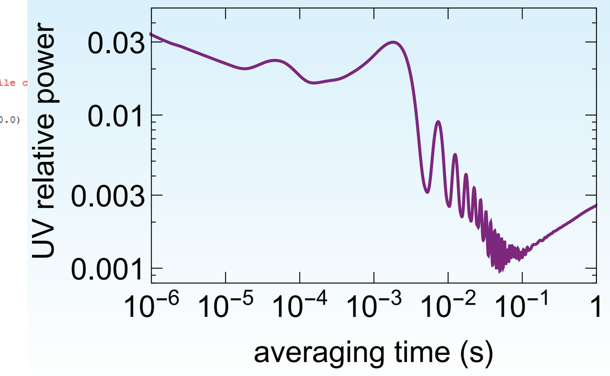


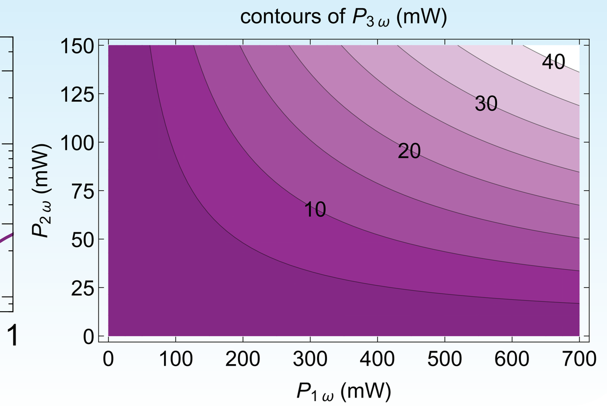


Computer control

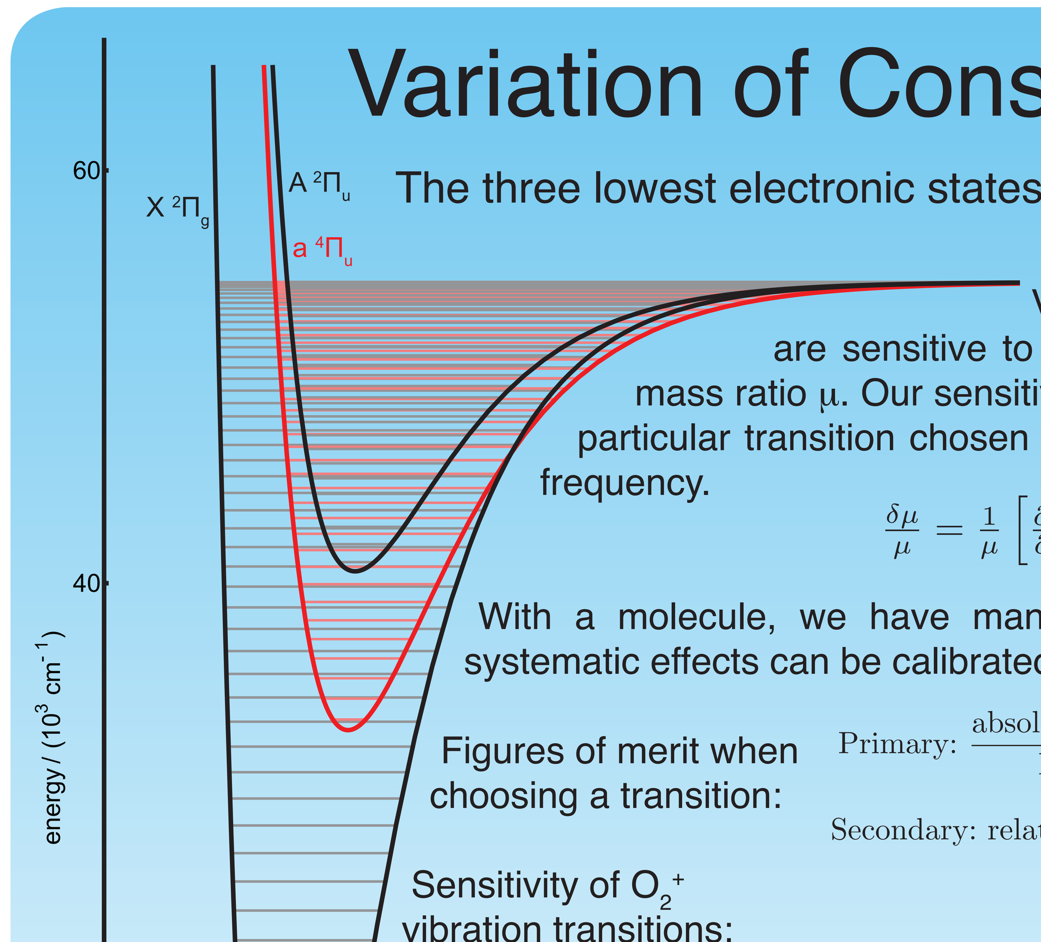
- Quantum Logic Ion Control (QLIC) python scripting language
- LabVIEW GUI
- Controls main sequencer (digital outputs), DDSes, analog outputs, PMT input







Variation of Constants



The three lowest electronic states of O_2^+

Vibration and rotation energy levels are sensitive to variation in the proton-to-electron mass ratio µ. Our sensitivity to any change depends on the particular transition chosen and how well we can measure its frequency.

$$\frac{\delta\mu}{\mu} = \frac{1}{\mu}\left[\frac{\partial\omega}{\partial\mu}\right]^{-1}\delta\omega = \left[\frac{\partial\omega}{\partial(\ln\mu)}\right]^{-1}\frac{\Gamma}{S/N}$$

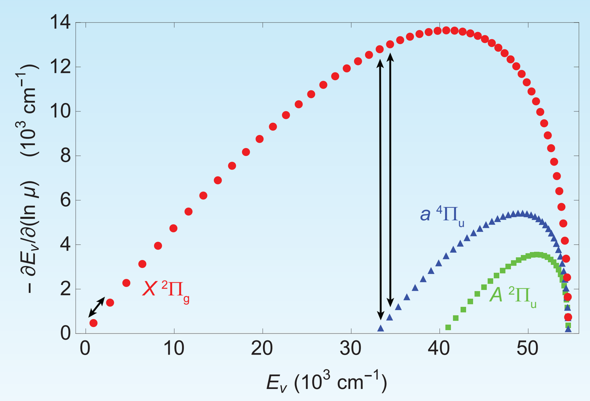
With a molecule, we have many transitions available, so many systematic effects can be calibrated in situ.

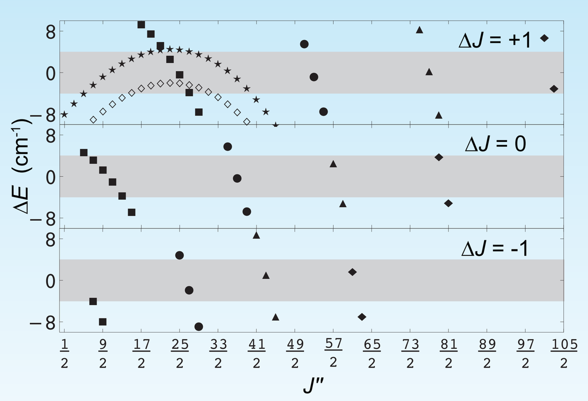
Figures of merit when choosing a transition:

$$\text{Primary: } \frac{\text{absolute sensitivity}}{\text{linewidth}} = \left[\frac{\partial\omega}{\partial(\ln\mu)}\right]\frac{1}{\Gamma}$$

$$\text{Secondary: relative sensitivity} = \left[\frac{\partial\omega}{\partial(\ln\mu)}\right]\frac{1}{\omega}$$

Sensitivity of O_2^+ vibration transitions:

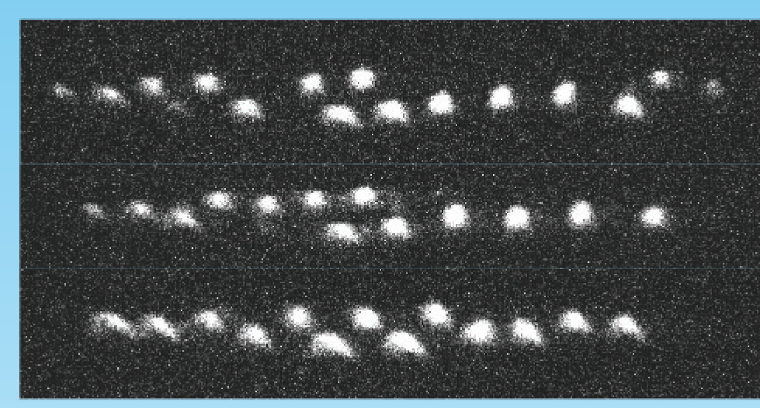




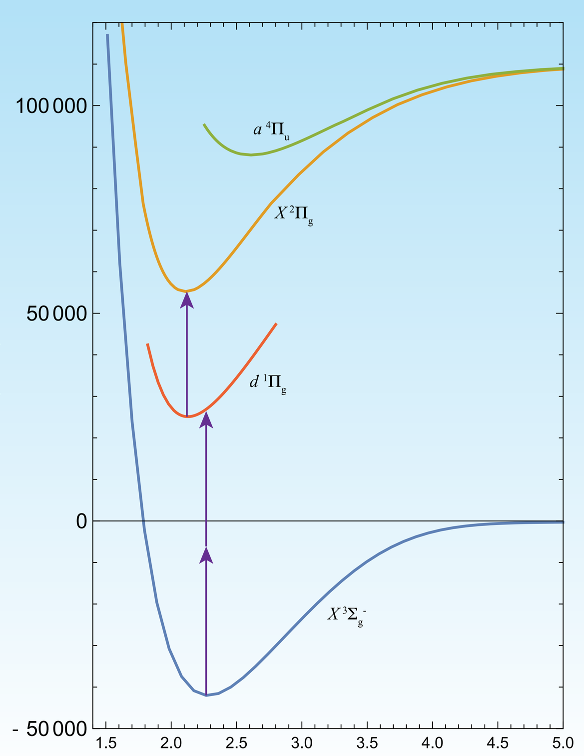
Phys. Rev. A **94**, 050101(R) (2016)

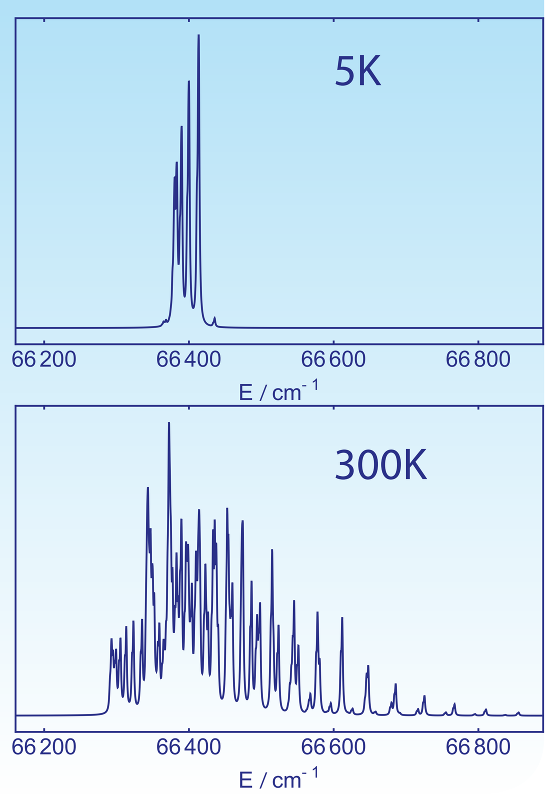
Loading O_2^+

We have successfully leaked O_2 into the trap and ionized by electron impact. The image series at right shows O_2^+ (and possibly O^+) in a crystal with Be⁺. The dark ions are identified by adjusting the radial trap parameters to make the trap unstable in a mass-selective way.



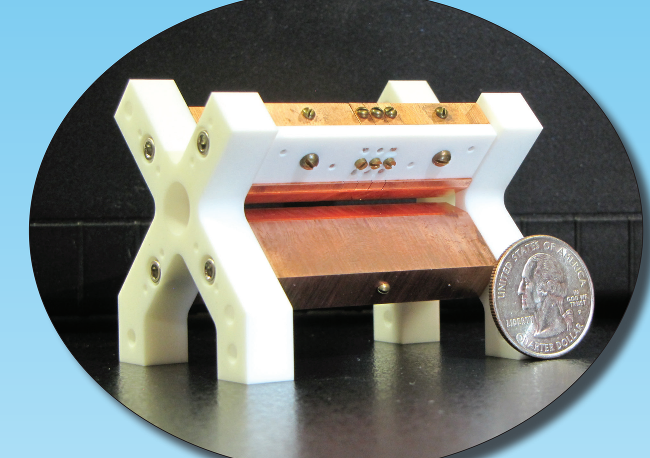
In the future, we will state-selectively load O_2^+ by photoionization. Using a doubled pulsed dye laser, two 296.5 – 303.5 nm photons excite from the ground $X\,^3\Sigma_g^-$ state to the $d\,^1\Pi_g$ state. An extra photon excites to the ion $X\,^2\Pi_g$ state, preserving rotation. At right are plots showing the X-to-d excitation spectra at room temperature and 5K, as in a pulsed beam.

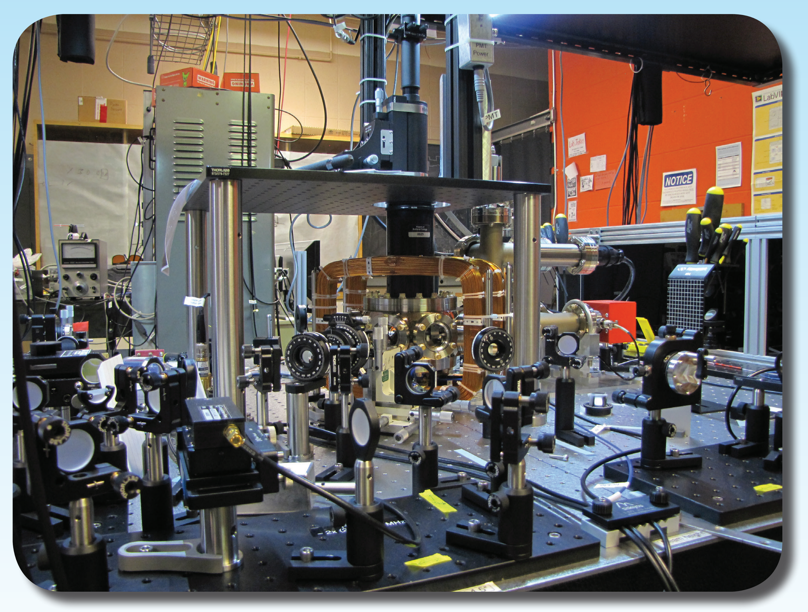




The apparatus

- UHV chamber with laser, imaging, and electrical access
- Beryllium wire ovens
- Precision leak valve for gas introduction
- Electron emitter for impact ionization of beryllium and background gas
- Trap parameters: $r_0 = 1.2$ mm, $z_0 = 1.5$ mm, $\Omega_{rf} = 2\pi(35\ \mathrm{MHz})$





Acknowledgments

Many undergraduate students have contributed to this work. In the past year, we have been aided by Christian Pluchar, Lauren Weiss, and Marissa Radensky.

This work has been funded by the National Science Foundation (CAREER, PHY-1255170) and the Amherst College Dean of the Faculty.

For more information, visit https://dhanneke.people.amherst.edu/