Toward All-Optical Loading of Co-Trapped Be^+ and O_2^+

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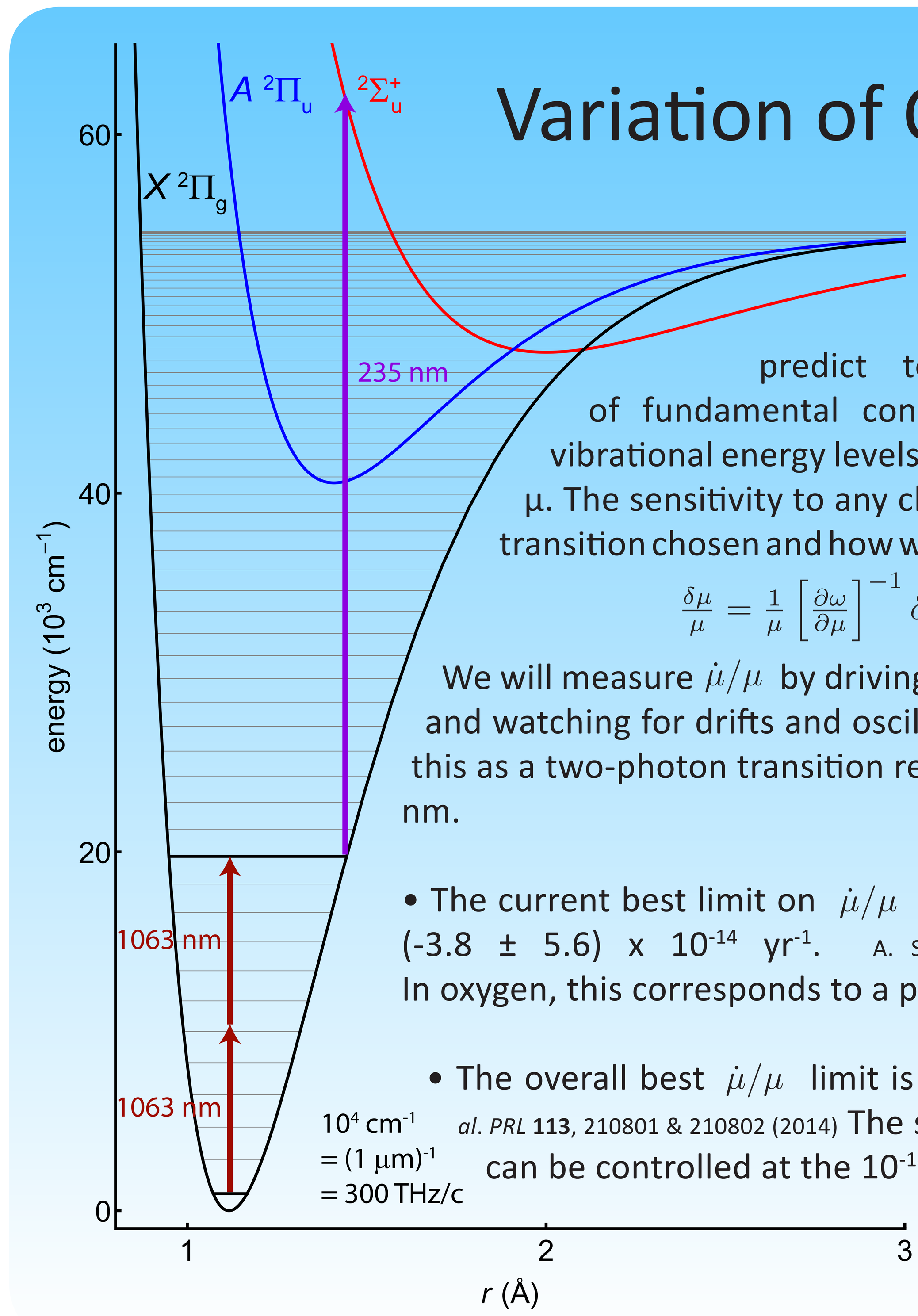
Variation of Constants



Some extensions to the Standard Model, especially dark matter and quantum gravity models, predict temporal or spatial variation of fundamental constants. In diatomic molecules, vibrational energy levels are sensitive to time variation of μ. The sensitivity to any change depends on the particular transition chosen and how well we can measure its frequency.

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

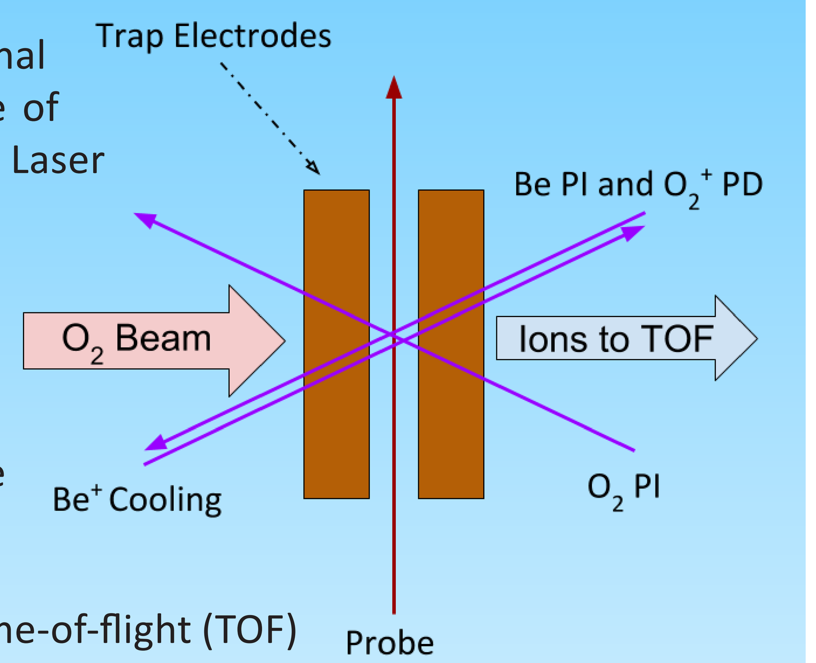
We will measure $\dot{\mu}/\mu$ by driving the v = 0 ↔ 11 transition in O_2^+ and watching for drifts and oscillations of the frequency. Driving this as a two-photon transition requires an optical source at 1063 nm.

- The current best limit on $\dot{\mu}/\mu$ from a molecular experiment is $(-3.8 \pm 5.6) \times 10^{-14}$ yr^{-1}. A. Shelkovnikov, *et al. PRL* **100** 150801 (2008) In oxygen, this corresponds to a precision of 12 Hz.
- The overall best $\dot{\mu}/\mu$ limit is $<10^{-16}$ yr^{-1}. Godun, *et al.* & Huntemann, *et al. PRL* **113**, 210801 & 210802 (2014) The systematic shifts in our molecule can be controlled at the 10^{-18} level.

Experimental Sequence

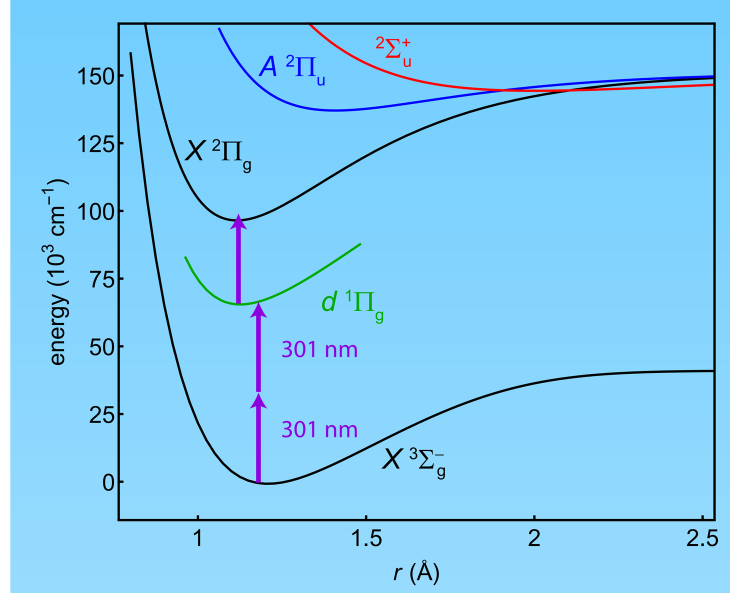
The initial experiment to measure $\dot{\mu}/\mu$ consists of four main steps.

1. Load a few dozen Be^+ ions and rovibrational ground state O_2^+ ions into a trap by use of resonance-enhanced photoionization. Laser cool to a Coulomb crystal.
2. Probe the v = 0 - 11 transition through a two-photon excitation at 1063 nm.
3. Photodissociate (PD) the O_2^+ ions in the excited vibrational state to O + O^+
4. Dump the contents of the trap into a time-of-flight (TOF) mass spectrometry arm. Presence of 16 amu particles confirms the v = 0 - 11 transition was driven.



Trapped and sympathetically cooled O_2^+ ions are a promising system for precision measurements, optical frequency metrology, and searches for new physics. We describe our techniques to load O_2^+ along with Be^+ coolant ions through resonance-enhanced photoionization. For beryllium, a custom-designed monolithic doubling cavity generates 235 nm light for single-color 1+1 ionization on the $^1S_0 \rightarrow {}^1P_1$ transition. In O_2, a cold molecular beam is photoionized via single-color 2+1 REMPI on the $X\ ^3\Sigma_g^- \rightarrow\rightarrow d\ ^1\Pi_g \rightarrow X\ ^2\Pi_g\ (O_2^+)$ transition. This transition is vibrationally selective and loads ions in a small number of rotational states. We describe initial work conducting spectroscopy of the molecular transition and plans for integrating the cold beam into our trap.

O_2^+ Photoionization

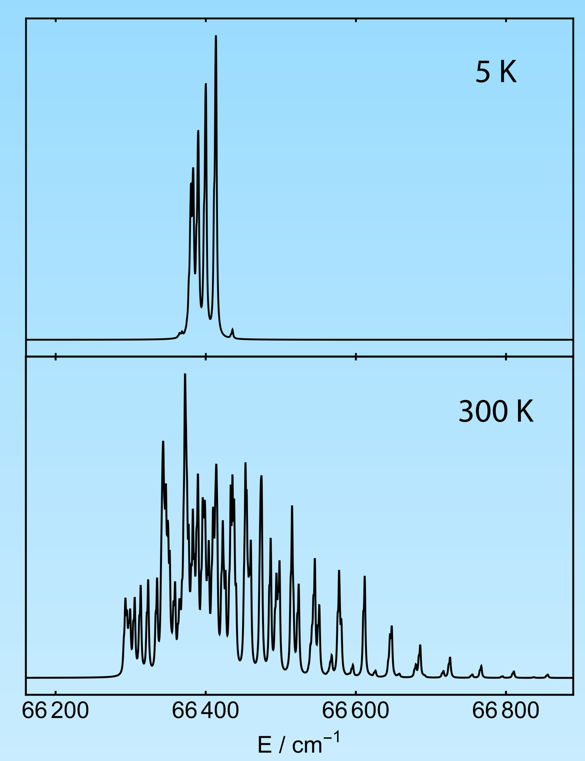


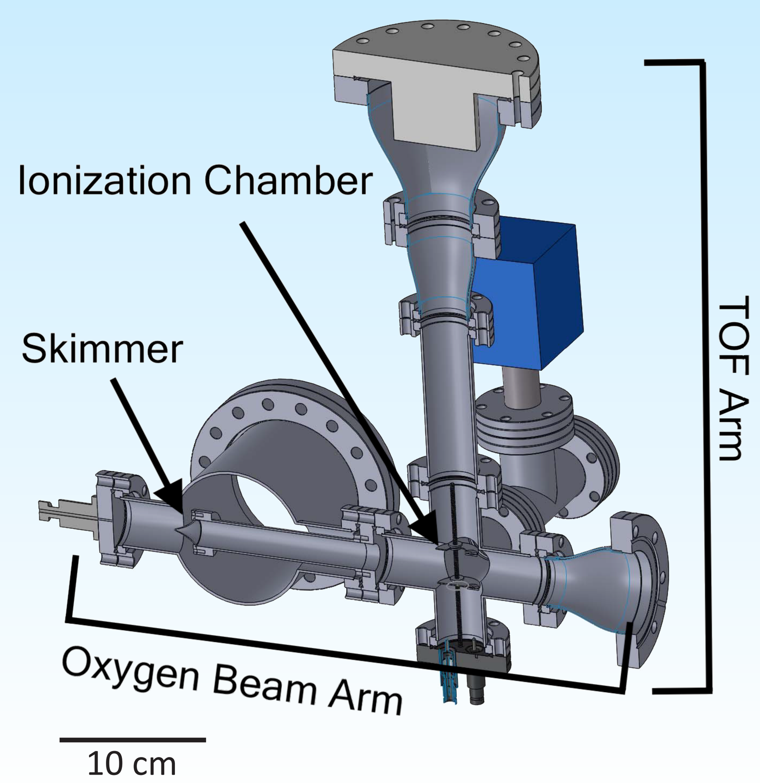
Sympathetic cooling does not affect the internal degrees of freedom in O_2^+, but we require ions in the ground rovibrational state for the $\dot{\mu}/\mu$ measurement. Accordingly, we will state-selectively produce O_2^+ by photoionization (PI) before translationally cooling to produce internally and externally cold ions.

Using a doubled pulsed dye laser, two 296.5 – 303.5 nm photons excite neutral molecules from the ground $X\ ^3\Sigma_g^-$ state to the $d\ ^1\Pi_g$ state. A third photon strips off an electron to create ions in the $X\ ^2\Pi_g$ state.

A third photon can hit the ionization threshold at < 325 nm. Vibrational selectivity is ensured by diagonal Franck-Condon factors. We expect population in six rotational states, including our desired state.

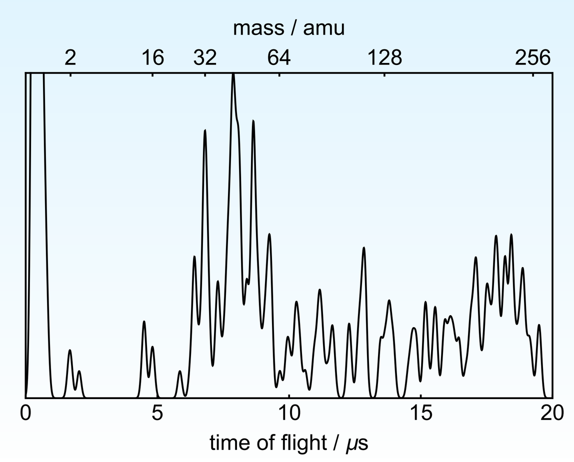
These plots show the two-photon *X*-to-*d* excitation spectra at room temperature and 5K, as in a pulsed beam. Working with a cold initial set of molecules both simplifies the spectrum and can be used to produce a higher percentage of ground state ions.



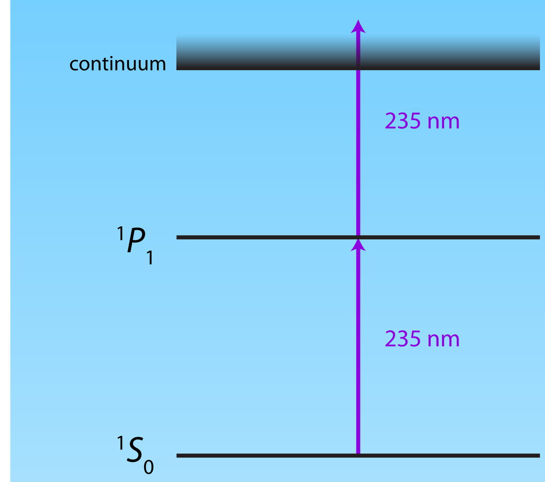


Our first step is to remeasure the PI spectrum by use of a pulsed supersonic beam. The beam can approach 5K temperatures.

Below is our first time-of-flight ion signal. We see oxygen at 6.8 μs, and many heavier ions.



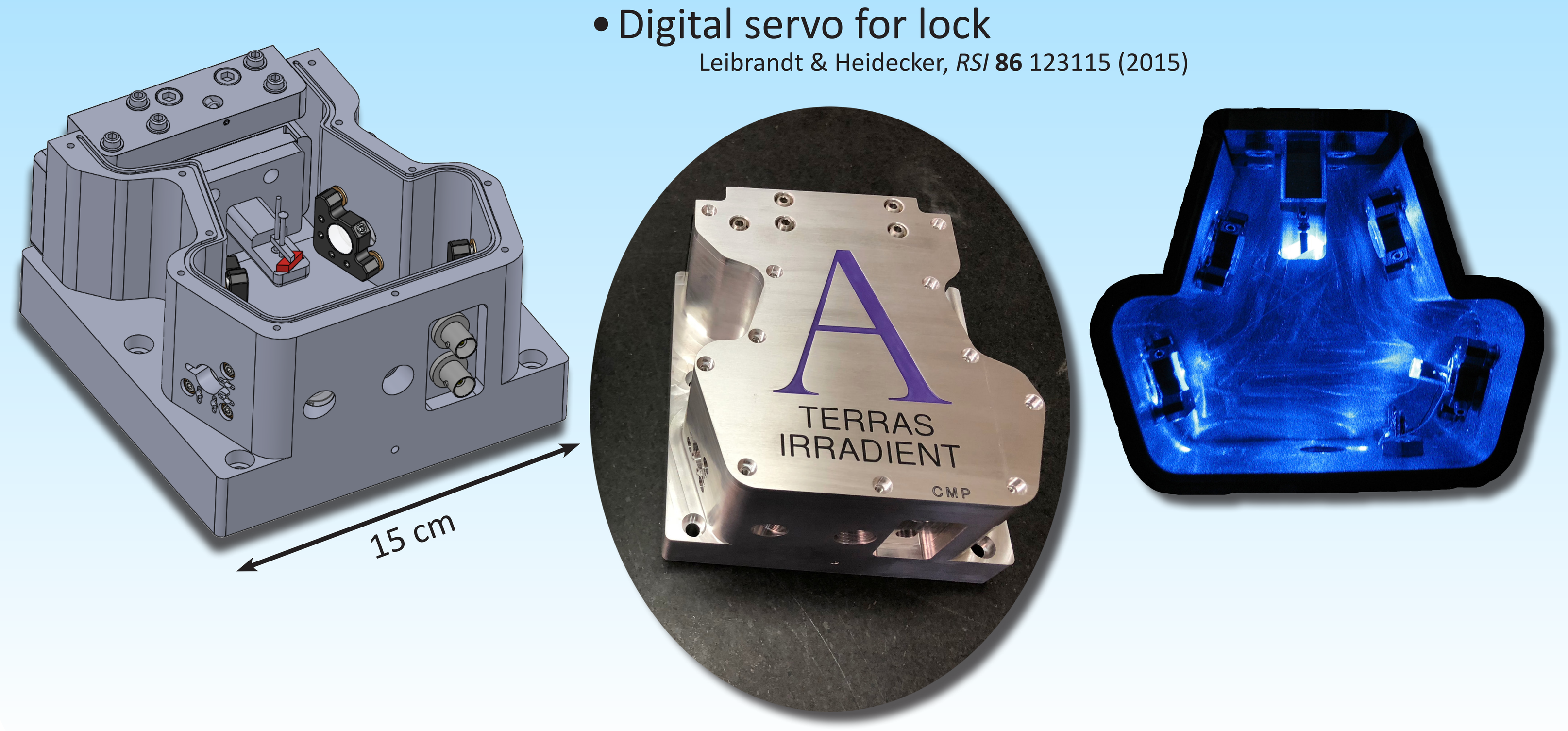
Beryllium Photoionization laser



Beryllium ions sympathetically cool the molecular ions to form Coulomb crystals at Doppler temperatures. We can load beryllium with either electron-bombardment or photoionization.

Photoionization laser:

- Commercial diode laser (470 nm, 100 mW)
- Second-harmonic generation in BBO
- Monolithic cavity design
  Similar to S. Hannig, *et al. RSI* **89** 013106 (2018)
- Digital servo for lock
  Leibrandt & Heidecker, *RSI* **86** 123115 (2015)



The apparatus

- UHV chamber with laser, imaging, and electrical access and a precision leak valve
- Beryllium wire ovens
- Next up: integrate molecular beam and time-of-flight arm

Acknowledgments

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