Towards quantum control of molecular ions

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Many atoms and molecules possess interesting spectroscopic transitions, but lack dissipative transitions useful for control and detection of internal states. In particular, molecules are candidates for quantum memories, low-temperature chemistry studies, tests of fundamental symmetries, and searches for time-variation of fundamental constants, but most lack a convenient cycling transition. By co-trapping a molecular ion with an atomic ion, the atom can provide all dissipation and detection. We present a system capable of such quantum control and report progress towards its use. We also present candidate molecules with analysis of potentially interesting transitions and systematic effects.

Quantum logic spectroscopy

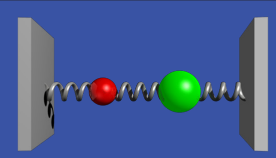
Leveraging quantum information processing techniques for precision measurement

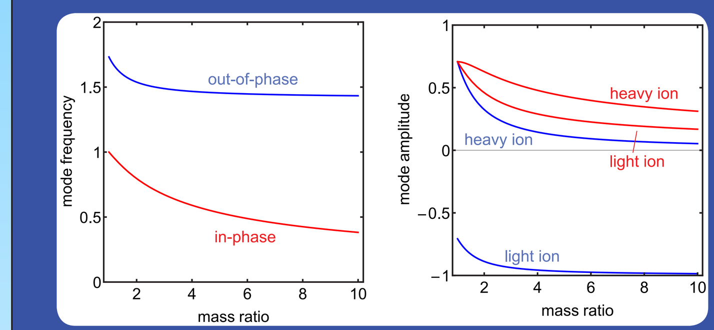
Atomic logic ion provides all dissipation
Target ion has an interesting spectroscopic transition

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

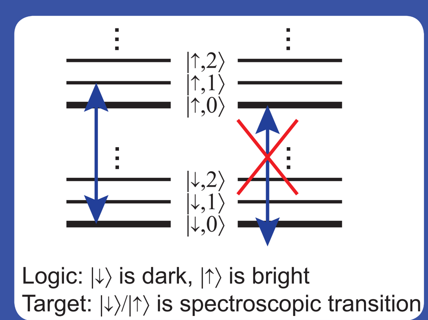
Our interest: molecules
- Quantum control of rotation states
- Rotation spectroscopy
- Quantum memory
- Tests of molecular quantum theory
- Time variation of fundamental constants
- Symmetry tests (P, T)

Normal modes:
an information bus shared by both ions





Conditional sideband excitation
read/write to info bus



Beryllium logic ion

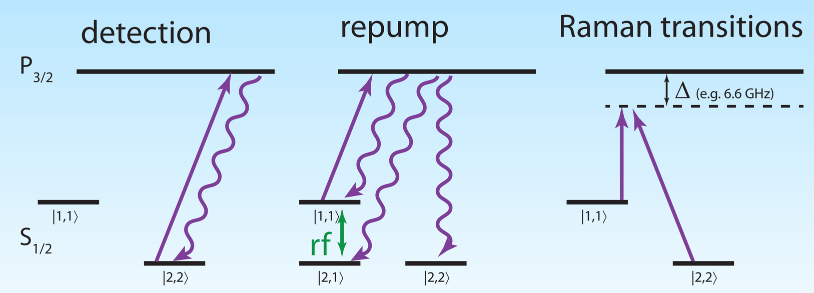
- Dissipation via photon scattering
- Hyperfine qubit
- Single isotope
- Ideal for lighter target ions

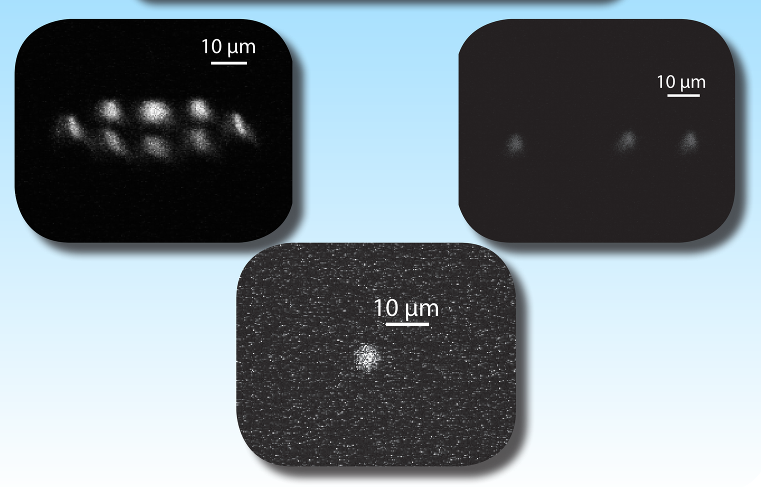
$^9Be^+$

$I = 3/2$

$\Gamma = 2\pi(19.4\ \mathrm{MHz})$

$\nu_{\mathrm{hfs}} = 1.25\ \mathrm{GHz}$

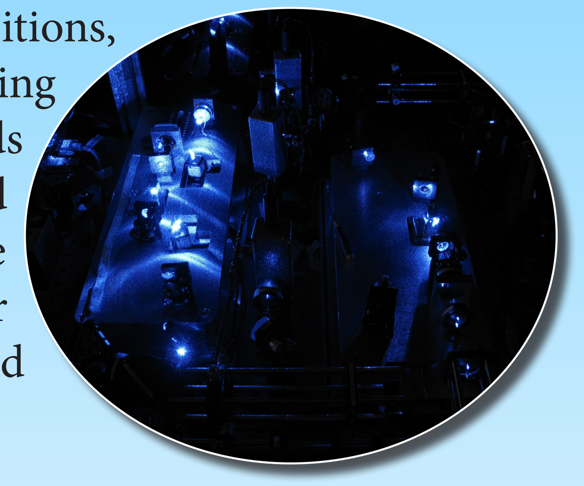


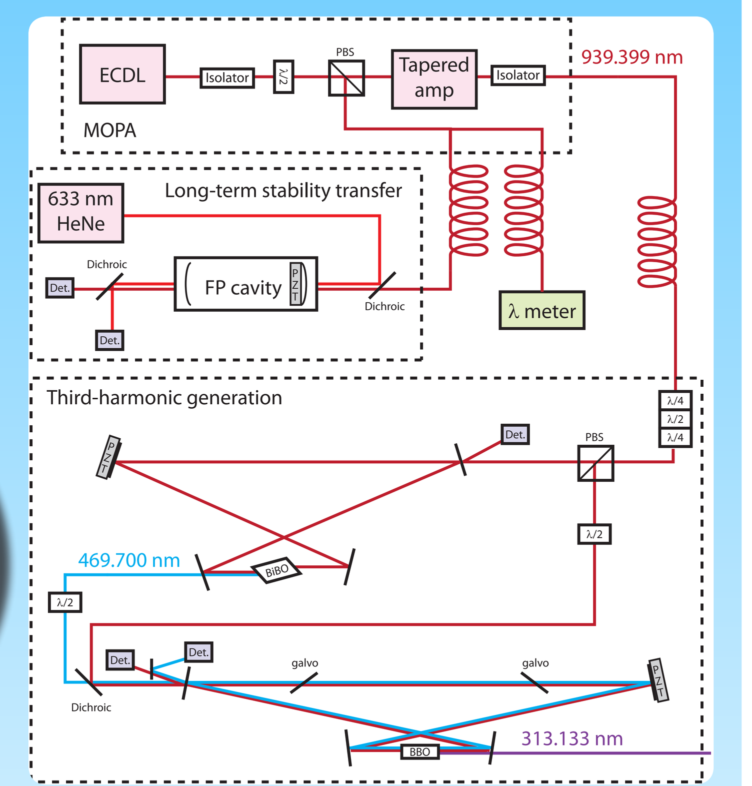


Quantum control of the logic ion

Lasers

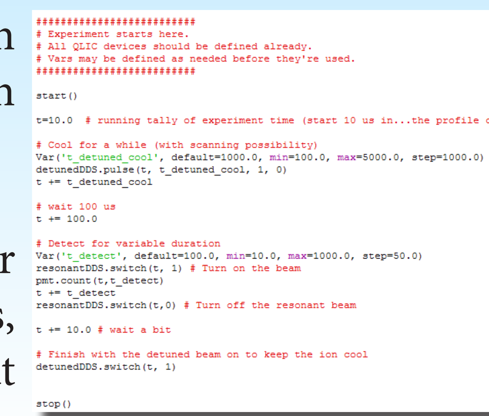
- Triple 939 nm diode laser to 313 nm (second-harmonic generation followed by sum-frequency generation)
- Transfer stability of HeNe to ECDL
- Laser is 6.6 GHz off-resonance for Raman transitions, but modulating the ECDL adds a sideband on resonance for Doppler cooling and detection.

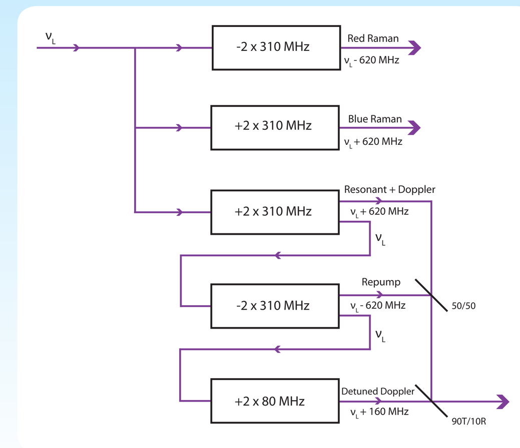




Computer control

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

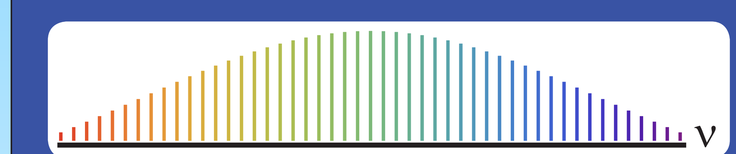




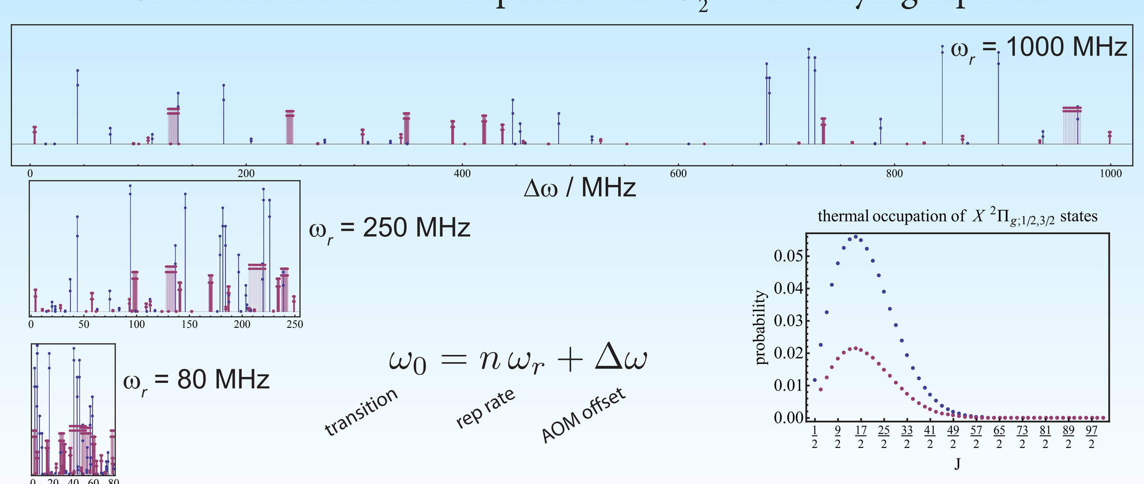
Rotation state qubits

Benefits of a homonuclear diatomic molecule
- Rotation transitions dipole-forbidden
- AC Stark shift from ion trap suppressed
- Blackbody shift suppressed
- Vibration transitions dipole-forbidden (won't accidentally drive with Raman laser)
- Choose J, M_J states to suppress magnetic-field-induced decoherence
- Primary decoherence from collisions?

Pulsed laser
- Span rotation transitions
  100 fs pulse ~ 4 THz BW
- Scan comb teeth with AOM
- No offset lock needed

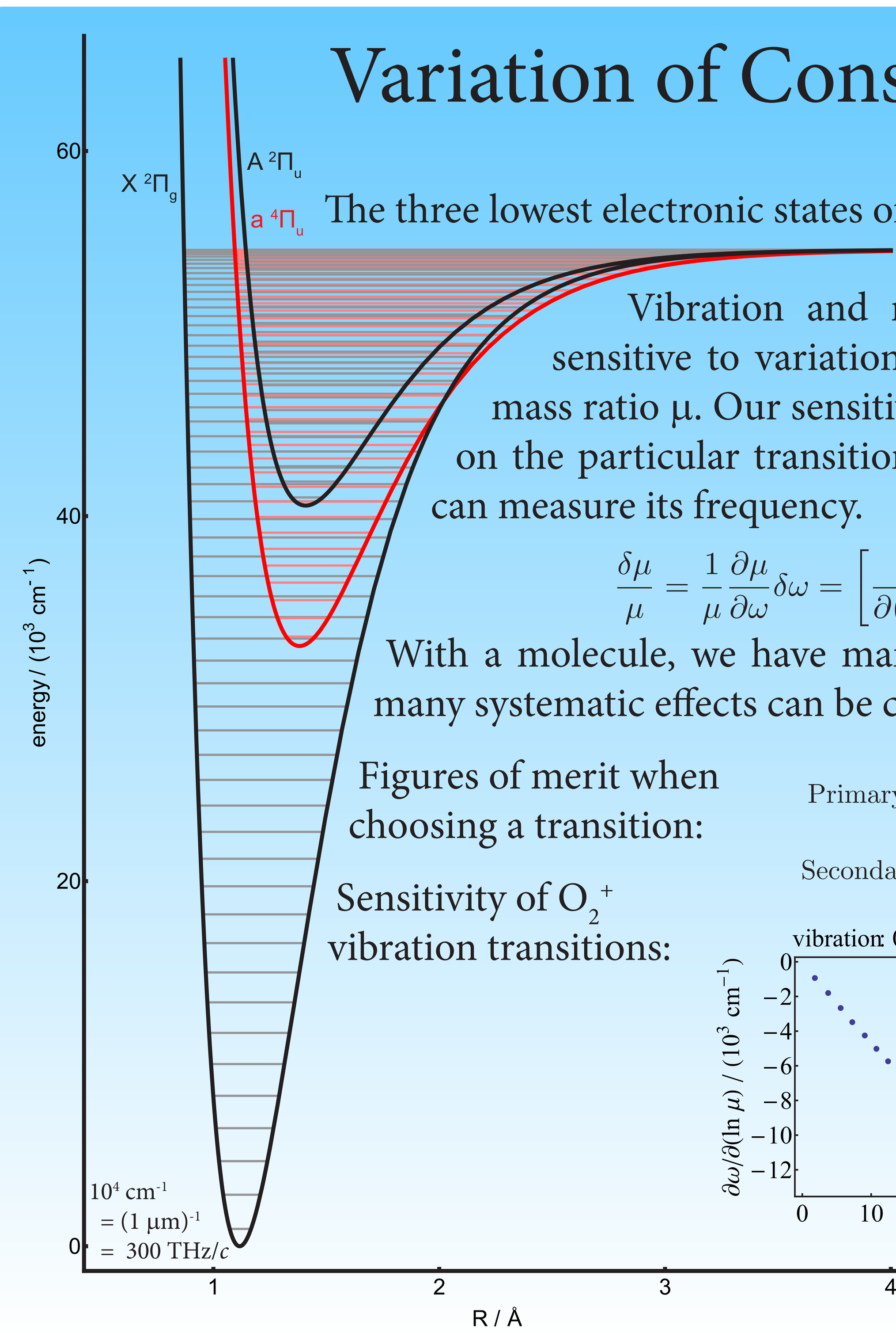


Simulations of thermal spectrum of O_2^+ with varying rep rates



Simulation is at 5 G to show Zeeman splitting.

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.

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

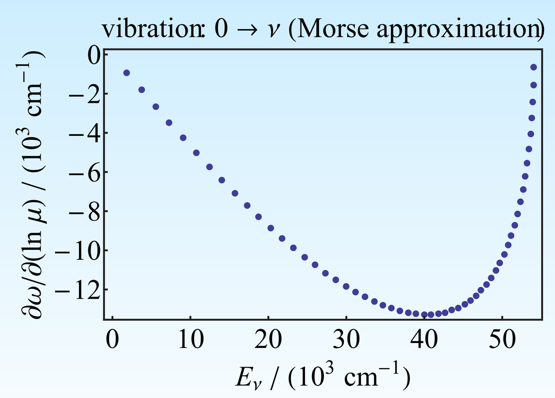
With a molecule, we have many transitions available, so many systematic effects can be calibrated in situ.

Figures of merit when choosing a transition:

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

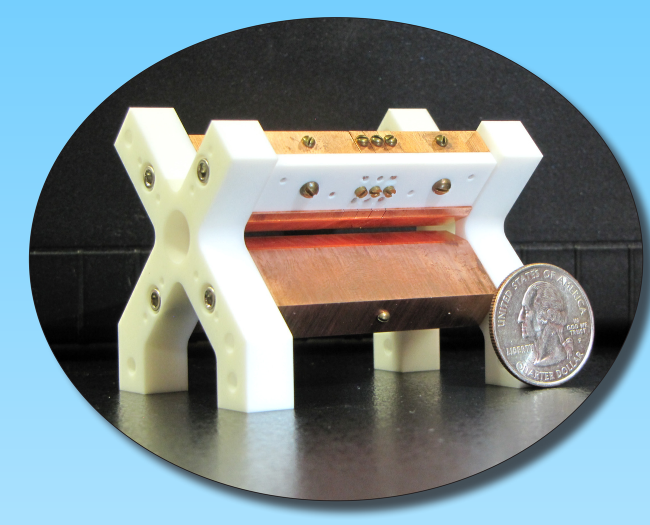
$$\text{Secondary: relative sensitivity} = \left[\frac{\partial\omega}{\partial(\ln\mu)}\right]\frac{1}{\omega}$$

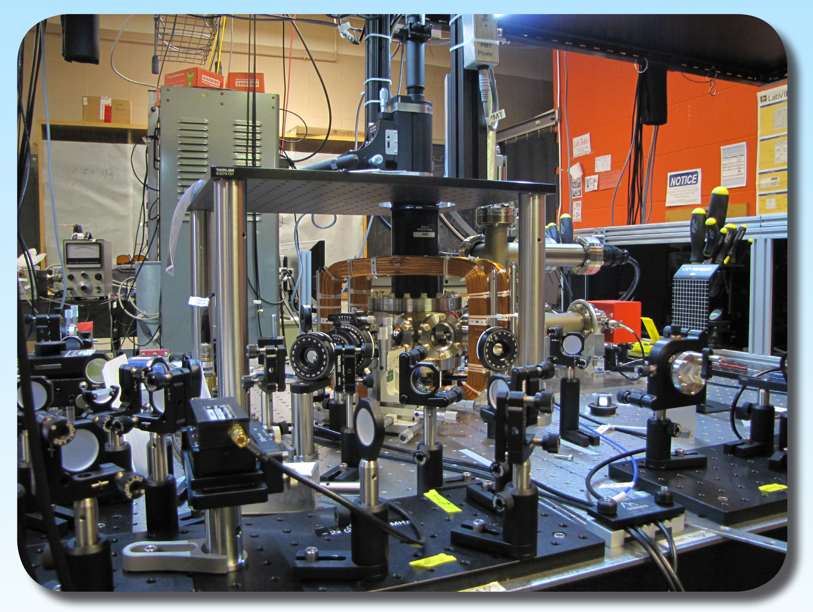
Sensitivity of O_2^+ vibration transitions:



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, $\Omega_{rf} = 2\pi(14 – 40\ \mathrm{MHz})$





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