Molecular hydrogen ions, the proton-electron mass ratio and the proton size

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Motivation

- Proton-electron mass ratio μ : fundamental quantity, sets scale of vibrations and rotations in atoms, molecules and bulk material
- Standard Model describes structure of nuclei, atoms, molecules (latter primarily QED, but also QCD)
- QED for simple systems (H, H_2^+, HD^+) has reached accuracy ~10^{-10} limited substantially by non-QED contributions (μ, internal structure proton & deuteron)
- Compare measurements H_2^+, HD^+ at ~10^{-10} accuracy with theoretical calculations to test QED & extract improved values for μ, proton Zemach radius, deuteron electric quadrupole moment
- Long term perspective: HD^+ spectroscopy at <10^{-15}, comparison with optical clocks to test constancy of μ [7]

Approach

Determination of μ from some observable $A = A(\mu)$ in three steps :

1. QED theory provides function $A(\mu)$
2. High-precision measurement of value A_m
3. Adjust $\mu \to \mu'$ so that $A(\mu') = A_m$

Current best determination of μ :

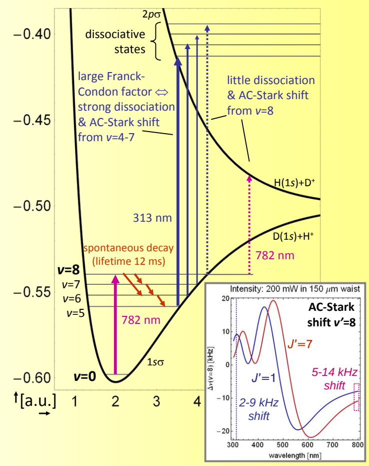
- Hydrogen-like ions in Penning trap:
  $A(\mu) = f_{\text{spin-flip}}/f_{\text{cyclotron}} = -g\ \eta\ \mu$
- QED provides bound-electron g-factor; η known with sufficient accuracy from other experiments
- μ value found with relative accuracy 5.2×10^{-10} [1]
- CODATA06 recommended value:
  $\mu = 1836.15267247(80)$ (4.3×10^{-10})

Determine μ from vibrational spectroscopy of HD^+

Advantages HD^+

- HD^+ vibrational frequencies $\nu_i \equiv \nu_i(\mu)$
- Dipole-allowed overtones between long-lived (>10ms) vibrational states
- Detection: loss of HD^+ due to REMPD[2]
- v = 0, J = 0-5 populated by 300K BBR [8]
  $\Rightarrow$ many tens of rovibrational lines accessible to IR lasers
- Systematic shifts <100 kHz, uncertainties <<100 kHz [3]
  (100 kHz ~ 0.26 ppb @782nm)

'AC-Starkless' REMPD detection



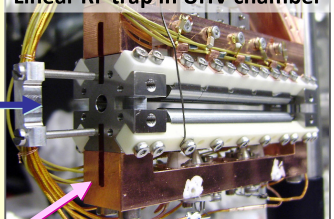
Experiment

Lasers

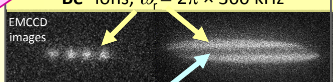
stable HeNe → transfer cavity → 626 nm dye laser → SHG (BBO) for laser cooling Be^+ @ 313 nm

Rb-locked DL1 → offset-locked DL2 → transfer cavity → Ti:S for HD^+ spectroscopy at wavelengths 780-790 nm ↔ fiber-based FC (Rb/GPS)

Linear RF trap in UHV chamber



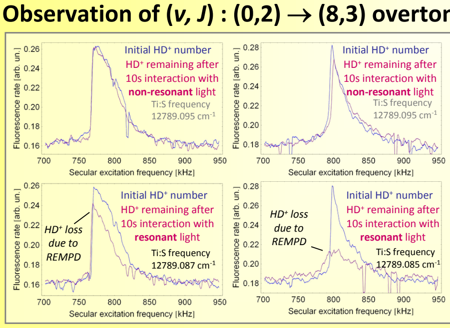
$^9Be^+$ ions, $\omega_r = 2\pi \times 300$ kHz



- Dark core: cold (~10 mK) HD^+ ions
- Indication of **trapped mK protons**
- **Determine N_{HD+}**: drive motion HD^+ and observe 313 nm fluorescence change due to heating of Be^+ [2]

Results

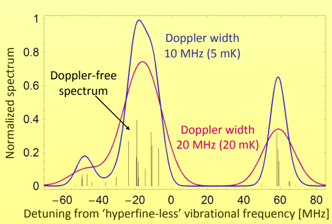
Observation of (v, J) : (0,2) → (8,3) overtone at 781.9166 nm



- First observation of $v = 0 \to v' = 8$ in HD^+
- Indication of resolved hyperfine structure
- Estimated HD^+ temperatures 5-20 mK
  ⇔ Doppler broadening to 10-20 MHz
- $v = 0 \to v' =$ 6,7,8,9 are within range Ti:S
  ⇒ >25 rovibrational lines may be measured

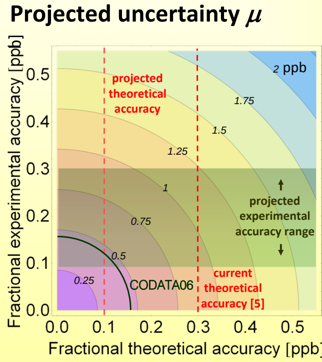
Simulated spectrum (v,J) : (0,2)→(8,3)

- Assume Doppler broadening 10-20 MHz
- Line split > 1:100 [3]
  ⇒ expect 100-200 kHz accuracy per line (100 kHz ~ 0.26 ppb @ 782 nm)
- Include theoretical hyperfine structure (current accuracy for HD^+ <50 kHz [6])
- Improve knowledge of HFS to <100 Hz through RF spectroscopy (see Outlook)



Outlook

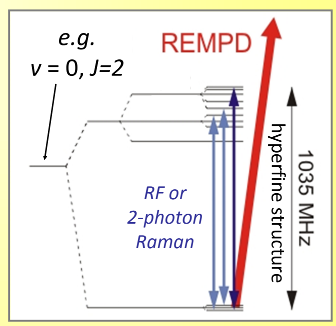
Projected uncertainty μ



Future experiments μ

- HD^+ ions in Lamb-Dicke trap
- ~10 Hz natural linewidth, so <<10^{-10} accuracy possible
- 'Molecular optical clock'
- Time-variation of μ?

RF spectroscopy and proton size



- Doppler free (Lamb-Dicke)
- Measure e-p spin-spin interaction with accuracy < 100 Hz
- Subtract QED terms (assume H_2^+ theoretical accuracy ~100 Hz [4])
- Remaining contributions: Zemach radius, proton polarizability (current inaccuracy ~500 Hz to HFS contribution)
  ⇒ ***Improved data on proton structure?***

References

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