Workshop on an Optical Clock Mission in ESA's Cosmic Vision Program
Düsseldorf 8. - 9. 3. 2007

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

High-resolution spectroscopy of cold molecular ions

B. Roth, J. Koelemeij, I. Ernsting, A. Wicht, S. Schiller
Heinrich-Heine-Universität Düsseldorf

Acknowledgements:
A. Nevsky, M. Okhapkin,
V. Korobov*, D. Bakalov+
* Joint Inst. Nuclear Research, Dubna
+ Institute for Nuclear Research and Nuclear Energy, Sofia

Why molecular clocks?

S.S. and V. Korobov, PRA 71, 032505 (2005)

- A comparison of an atomic optical clock to a molecular optical clock is (within the Standard Model) sensitive to all nongravitational interactions:

$$\frac{\Delta(\nu_{at}/\nu_{vib})}{\nu_{at}/\nu_{vib}} = b_\alpha \frac{\Delta\alpha}{\alpha} + b_\phi \frac{\Delta\phi}{\phi} + b_\Lambda \frac{\Delta\Lambda_{QCD}}{\Lambda_{QCD}}$$

$$b_\alpha, b_\phi, b_\Lambda \simeq O(1)$$

Energy scale of QCD

Higgs vacuum field

- In gauge unification theories the dependencies of α and Λ_{QCD} on U are correlated *(Damour 1999, Langacker et al, Calmet & Fritzsch, 2002)*

$$\frac{\Delta\Lambda_{QCD}}{\Lambda_{QCD}} \simeq 40 \frac{\Delta\alpha}{\alpha}$$

- **Molecular Clocks are very sensitive probes!**

Cold Molecules

- The first accurate optical frequency references were molecules: CH_4, OsO_4, I_2
- For precision spectroscopy, ultracold, trapped molecules are necessary

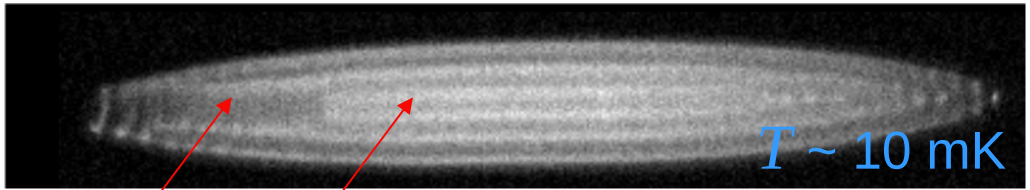
  - reduces various line broadening mechanisms
  - allows best control over and characterization of systematic effects
  - vibrational levels in the electronic ground state have lifetimes **10 ms to days**

- Progress in production and manipulation of cold molecules is strong:

  - Ultracold neutral diatomic molecules have been produced by photoassociation from ultracold atoms, e.g. Rb_2 *(Pillet et al, 1998)*
  - Trapping in an optical lattice demonstrated *(Rom et al. 2004)*
  - Molecular ions have been cooled and trapped by sympathetic cooling *(Aarhus/Düsseldorf)*
  - Cold Neutral dipolar molecules have been trapped in electric traps *(Rhinhuizen/Berlin/München)*
  - *…..*

Cold Molecular Ions

- Molecular ions can be easily produced and sympathetically cooled



*Blythe et al., PRL **95**,183002 (2005)*

- Large variety of molecular ions possible
  - By (electron-beam or photo-) ionization of neutral molecules
  - By chemical reactions
  - Can choose most suitable ones in terms of systematic shifts, ease of spectroscopy,….
  - Few-electron molecules can be calculated ab initio, e.g. hydrogen molecular ions (H_2^+, HD^+, D_2^+), HeH^+, ….

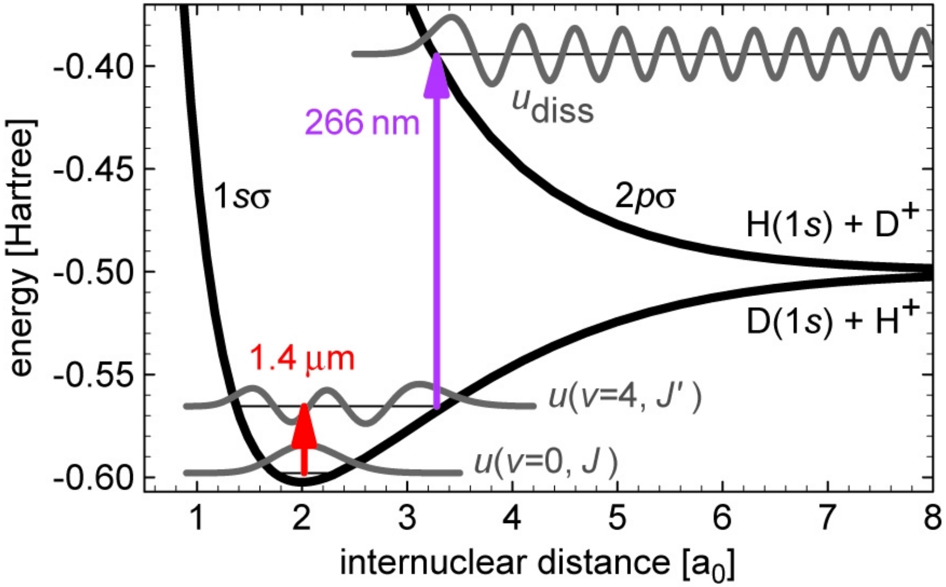
→ H_3^+ , H_2D^+, D_2H^+, ArH^+, N_2H^+, BeH^+, BeD^+, O_2H^+, BaO^+

Spectroscopy

☹ Electron shelving technique not applicable

☺ Options: - *Laser-induced reactions (see e.g. Gerlich et al, …)*
- *resonance enhanced multi-photon dissociation (REMPD)*
- *quantum logic spectroscopy (P. Schmidt et al., NIST)*
- *…*

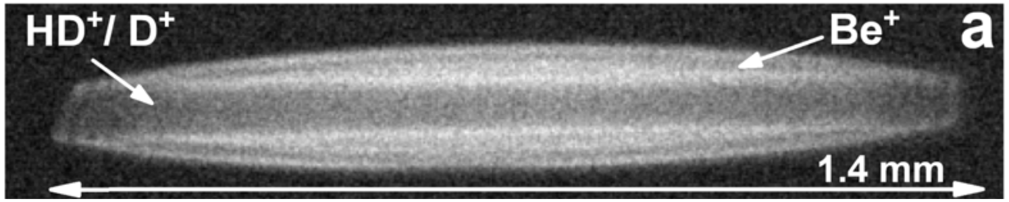
Ro-vibrational spectroscopy of cold HD^+



- Dipole-allowed transitions
- v = 0 to v = 4 overtone transition is accessible to diode laser
- Long lifetime ~ 10 ms
- No detectable fluorescence

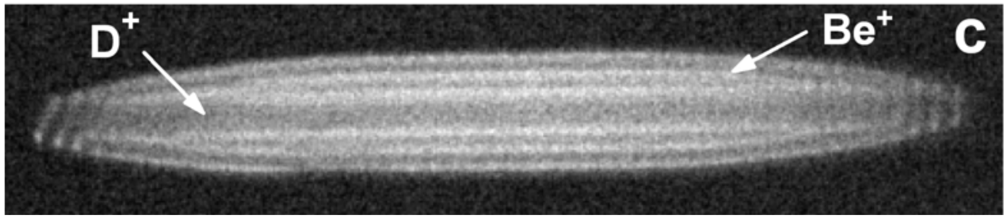
→ use state-selective photodissociation and measure number of remaining HD^+ ions

Beginning:



End:

- -

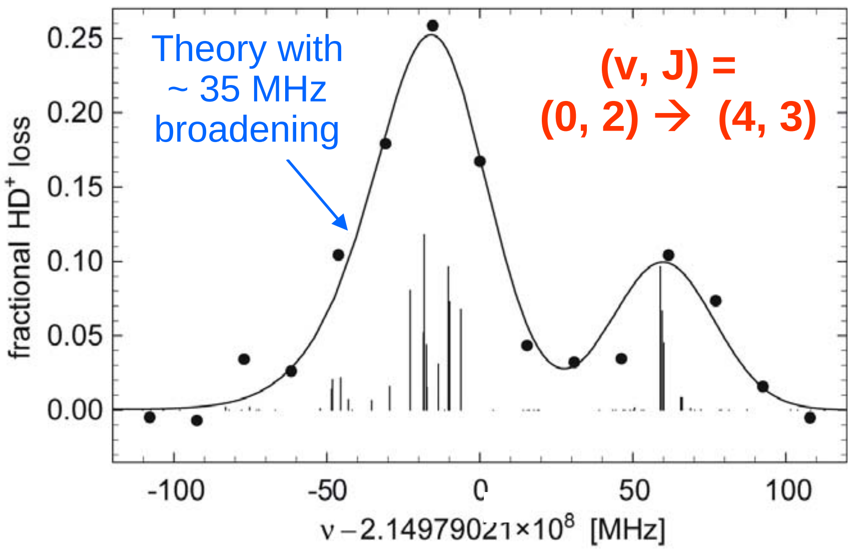


Results

B. Roth et al., Phys. Rev. A 74, 040501(R) (2006)
J. Koelemeij et al (subm.)

Residual linewidth:

- **unresolved hyperfine structure**
- **finite temperature**
- **excess micromotion**
- **laser linewidth**



Theory:
Ray & Certain 1976, Ryzlewicz et al. 1982, Carrington et al 1985, Bakalov et al. 2006

Recent results:

- measurement of transition frequency at 1.4 µm in agreement with ab-initio theory at < 10 ppb level

- estimate of systematic effects

  1.10^{-10} for our trap;

  but could be improved significantly
  (magentic field control,
  minimize micromotion,
  shutter light beams, etc.)