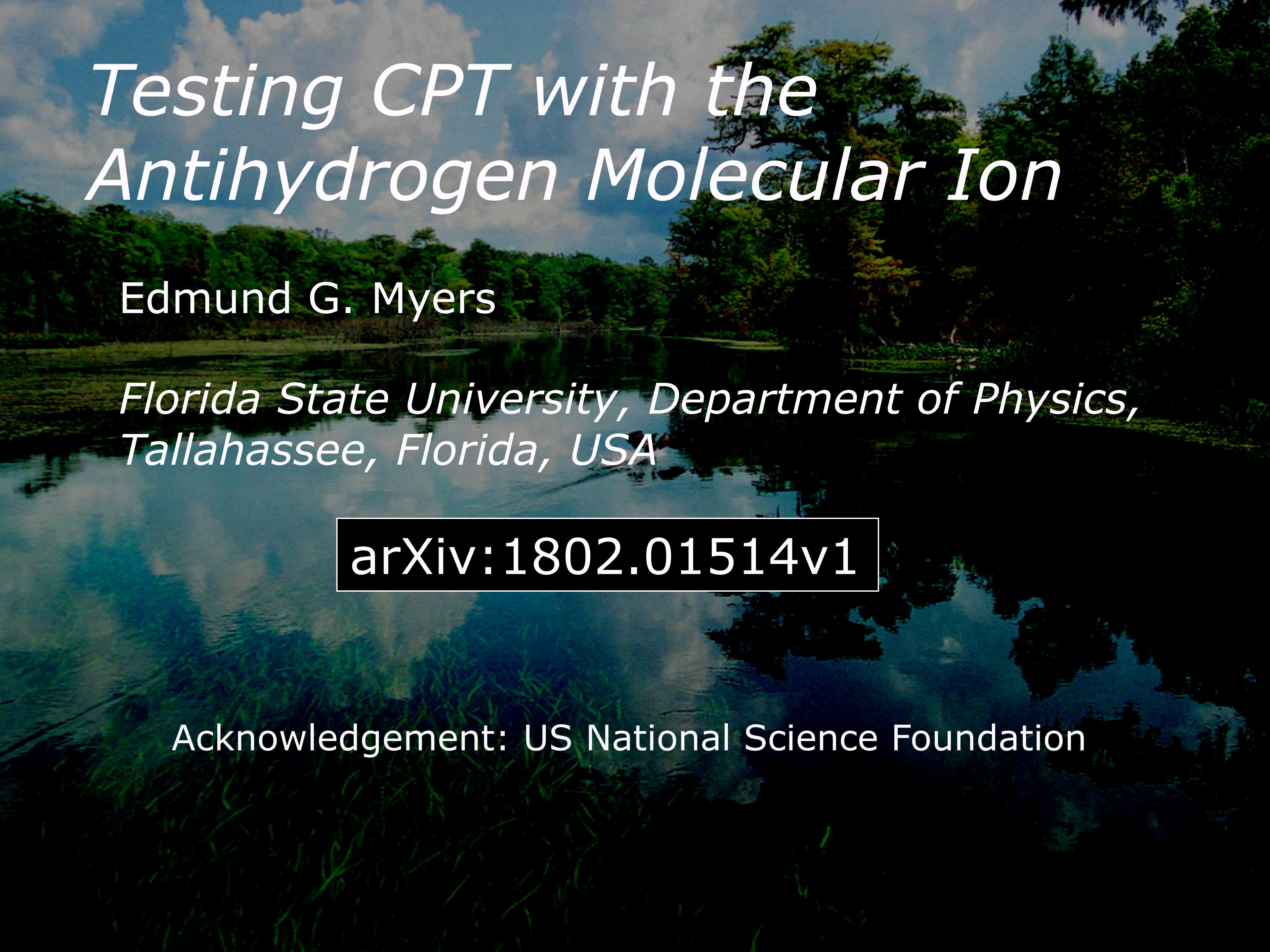


Testing CPT with the Antihydrogen Molecular Ion

Edmund G. Myers

Florida State University, Department of Physics,
Tallahassee, Florida, USA

arXiv:1802.01514v1

Acknowledgement: US National Science Foundation

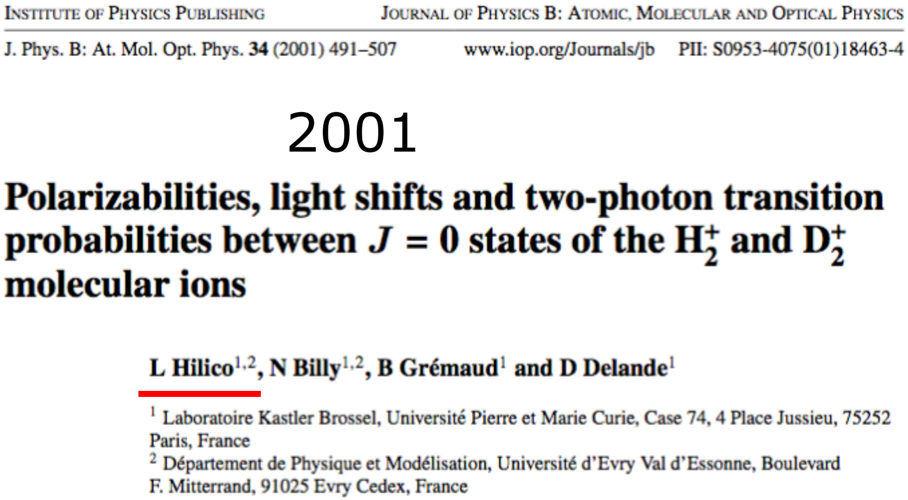
$\overline{\mathrm{H}}_2^-$ is the simplest anti-protonic ion with bound excited states

$\bar{p}\, e^+ \bar{p}$ (*compare with* H_2^+ $p\, e^- p$)

Electronic ground state $^2\Sigma_{1/2}$

$\overline{\mathrm{H}}^+$ ($e^+ \bar{p}\, e^+$) has no bound excited states

H_2^+ Ro-Vibrational Spectroscopy $<10^{-16}$



Institute of Physics Publishing Journal of Physics B: Atomic, Molecular and Optical Physics

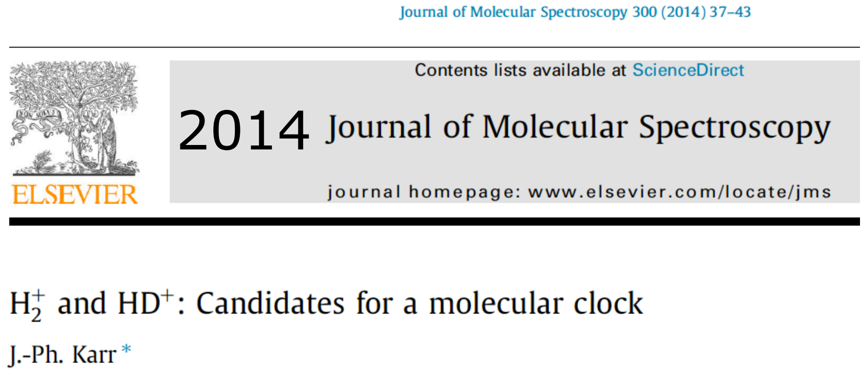
J. Phys. B: At. Mol. Opt. Phys. **34** (2001) 491–507 www.iop.org/Journals/jb PII: S0953-4075(01)18463-4

2001

Polarizabilities, light shifts and two-photon transition probabilities between $J = 0$ states of the H_2^+ and D_2^+ molecular ions

L Hilico[1,2], N Billy[1,2], B Grémaud[1] and D Delande[1]

[1] Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Case 74, 4 Place Jussieu, 75252 Paris, France
[2] Département de Physique et Modélisation, Université d'Evry Val d'Essonne, Boulevard F. Mitterrand, 91025 Evry Cedex, France



Journal of Molecular Spectroscopy 300 (2014) 37–43

Contents lists available at ScienceDirect

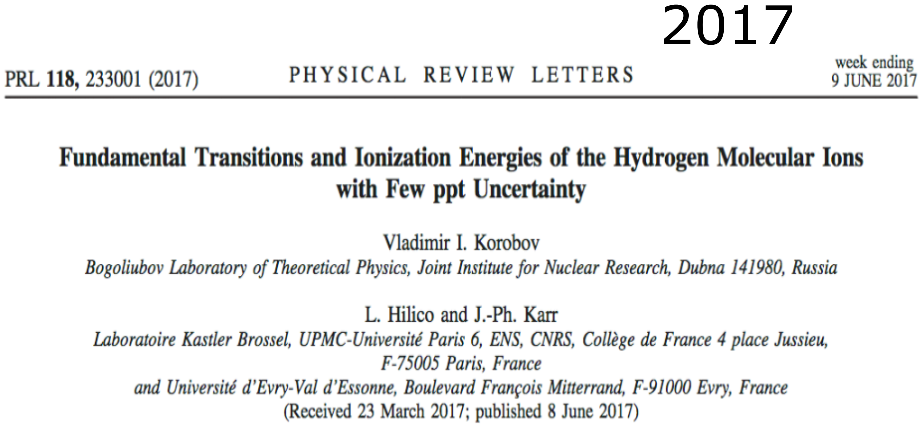
ELSEVIER

2014 Journal of Molecular Spectroscopy

journal homepage: www.elsevier.com/locate/jms

H_2^+ and HD^+: Candidates for a molecular clock

J.-Ph. Karr *



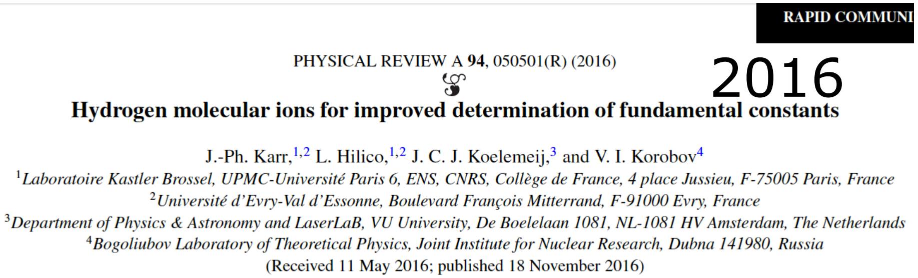
2017

PRL **118,** 233001 (2017) PHYSICAL REVIEW LETTERS week ending 9 JUNE 2017

Fundamental Transitions and Ionization Energies of the Hydrogen Molecular Ions with Few ppt Uncertainty

Vladimir I. Korobov
Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna 141980, Russia

L. Hilico and J.-Ph. Karr
Laboratoire Kastler Brossel, UPMC-Université Paris 6, ENS, CNRS, Collège de France 4 place Jussieu, F-75005 Paris, France
and Université d'Evry-Val d'Essonne, Boulevard François Mitterrand, F-91000 Evry, France
(Received 23 March 2017; published 8 June 2017)



RAPID COMMUNI

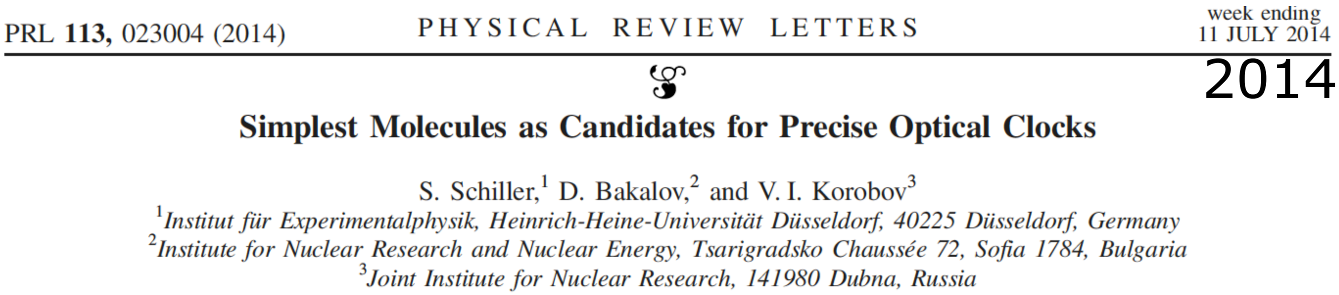
PHYSICAL REVIEW A **94,** 050501(R) (2016)

2016

Hydrogen molecular ions for improved determination of fundamental constants

J.-Ph. Karr,[1,2] L. Hilico,[1,2] J. C. J. Koelemeij,[3] and V. I. Korobov[4]

[1] *Laboratoire Kastler Brossel, UPMC-Université Paris 6, ENS, CNRS, Collège de France, 4 place Jussieu, F-75005 Paris, France*
[2] *Université d'Evry-Val d'Essonne, Boulevard François Mitterrand, F-91000 Evry, France*
[3] *Department of Physics & Astronomy and LaserLaB, VU University, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands*
[4] *Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna 141980, Russia*
(Received 11 May 2016; published 18 November 2016)



PRL **113,** 023004 (2014) PHYSICAL REVIEW LETTERS week ending 11 JULY 2014

2014

Simplest Molecules as Candidates for Precise Optical Clocks

S. Schiller,[1] D. Bakalov,[2] and V. I. Korobov[3]

[1] *Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[2] *Institute for Nuclear Research and Nuclear Energy, Tsarigradsko Chaussée 72, Sofia 1784, Bulgaria*
[3] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*

Tests of CPT using anti-hydrogen

Compare 1s-2s (2 photon) transition and
and 1s Hyperfine splitting (HFS)

Measurements on Hbar:
1s-2s to 2×10^{-12} (ALPHA 2017)
1s HFS to 4×10^{-4} (ALPHA 2017)

Measurements on H:
1s-2s to $\mathbf{4 \times 10^{-15}}$ (Garching 2011)
1s HFS to 7×10^{-13} (Paris-Sud, Orsay 2011, MASER)

1s-2s comparison measures $q(e^+)^4\, \boldsymbol{m(e^+)} - q(e^-)^4\, \boldsymbol{m(e^-)}$

Dependence on $\boldsymbol{m(e)/m(p)}$ through reduced mass correction, but is x1836 less sensitive

Why $H_2^+/\ \overline{H}_2^-$?

A) Best optical atomic clocks: (2018 record **2.5×10^{-19} !**)

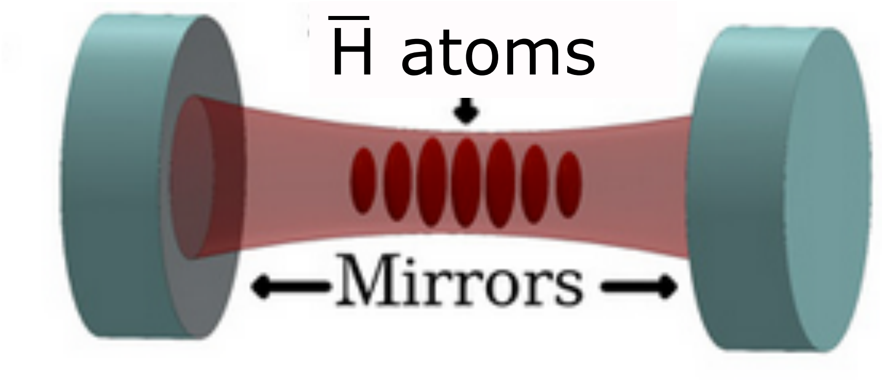
1) Single ion, e.g. Al^+, Yb^+

2) Ultra-cold atoms in an optical lattice, e.g. Sr, Yb

B) Working with neutrals is harder than ions…

Atom traps are ***very*** weak, inhomogeneous B…

Optical Lattice for H/$\bar{H}$?

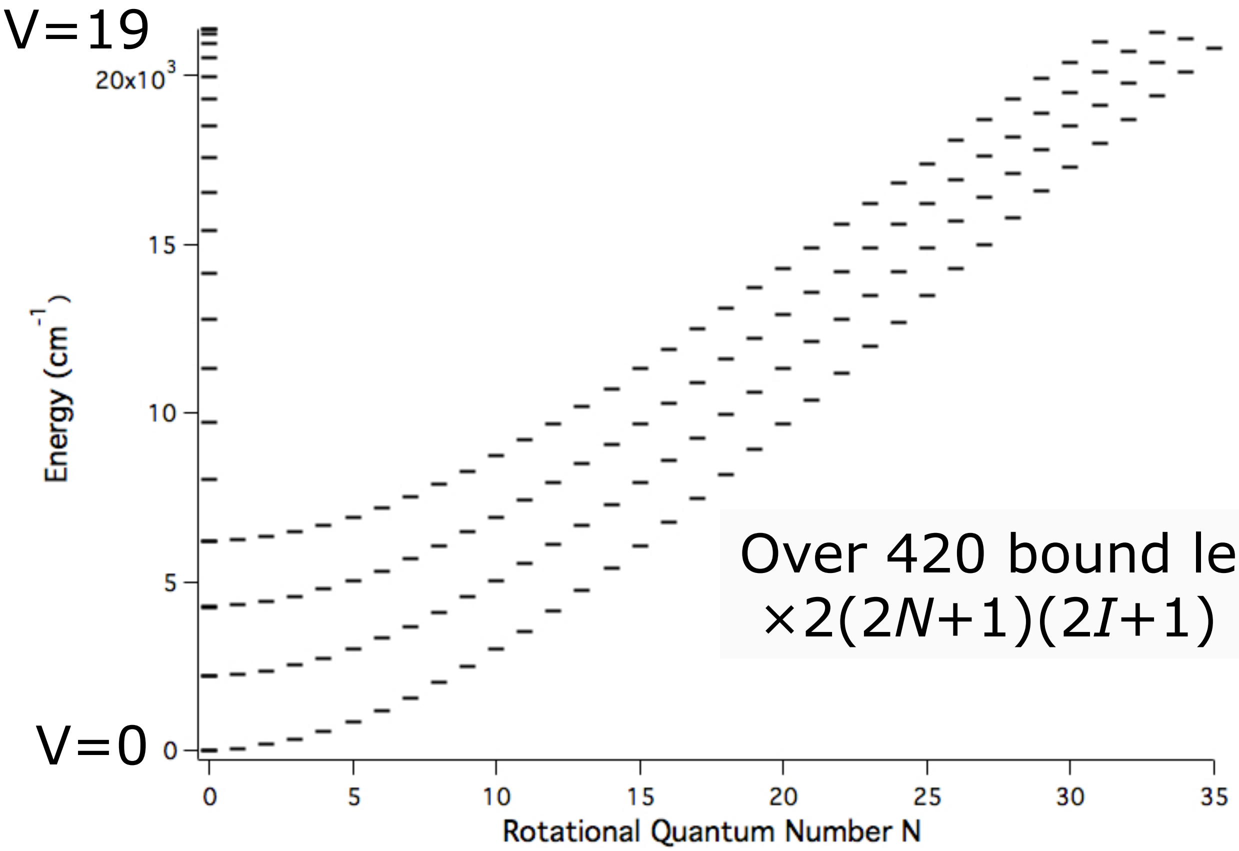


Need high intensity

Magic wavelength for 1s-2s is 513 nm
A. Kawasaki, PRA **92**, 042507 (2015)

Ideal: H and $\bar{H}$ in the same lattice!

H_2^+ Ro-vibrational levels



Over 420 bound levels
$\times 2(2N+1)(2I+1)$ sub-states

Pilon and Baye, J.Phys B (2012)

H_2^+ Ro-vibrational levels

Even N, $I=0$, Para; odd N, $I=1$, Ortho
Ortho, Para are “separate species” $\Delta N = 0,\pm 2$

Vibrational levels decay by *E2* transitions
Mean lifetimes are ~week, or longer

Many, very narrow (<μHz width) transitions ☺

But no fluorescence, how to detect? 😐

How to initialize the state? 😐

Continuous Stern-Gerlach effect to detect electron spin-flips

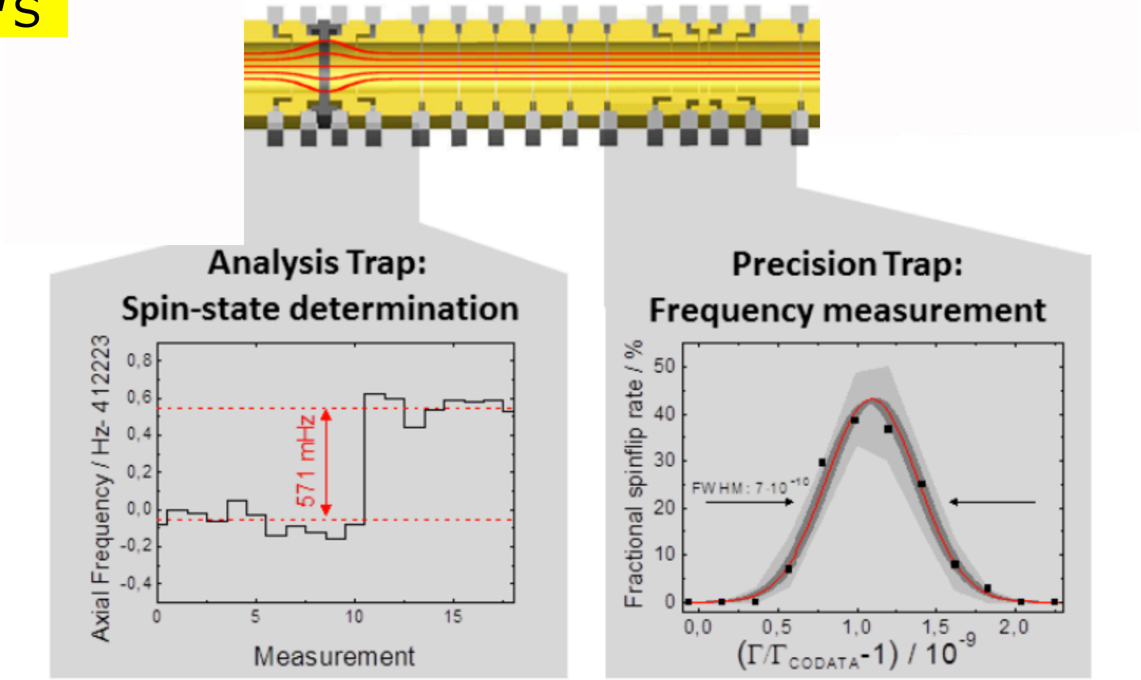
Sven Sturm *et al*, Nature 2014, $\boldsymbol{g}_{\mathbf{e}}(^{12}\mathrm{C}^{5+})$ to 3 x 10^{-11}

Identifies
e^{-} spin-state M_S

2 Penning traps

Analysis trap
Inhomogeneous B

Precision trap
Uniform B



Continuous Stern-Gerlach effect to detect electron spin-flips

Sven Sturm *et al*, Nature 2014, $\boldsymbol{g}_{\mathbf{e}}(^{12}C^{5+})$ to 3 x 10^{-11}

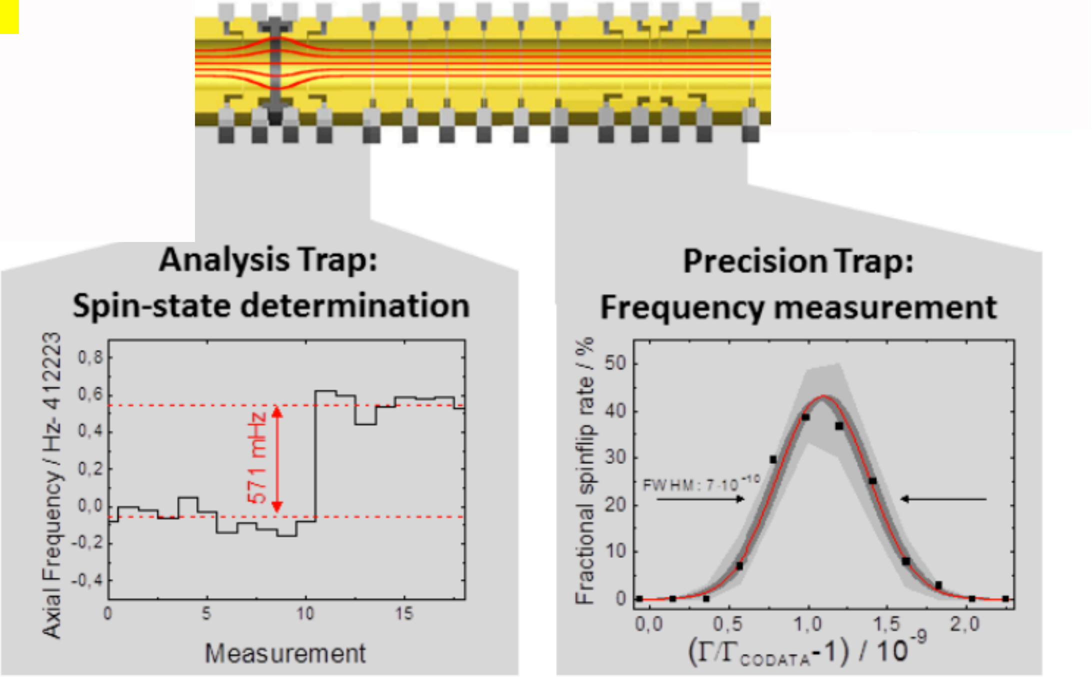
Identifies $e^{\pm}$ spin-state M_S

Will work for H_2^+ and $\bar{H}_2^-$

2 Penning traps

Analysis trap
Inhomogeneous B

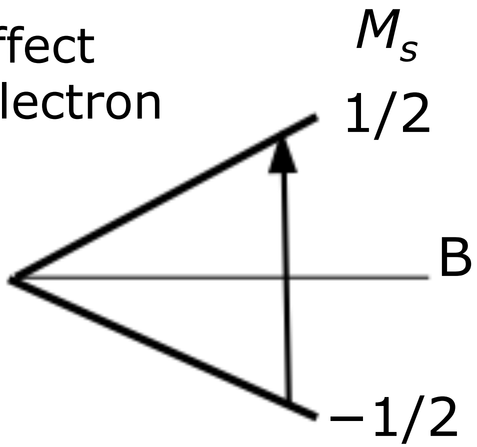
Precision trap
Uniform B



Bound $e^{\pm}$ magnetic moment of $\overline{\mathrm{H}}_2^-/\mathrm{H}_2^+$

$N=0$: no hyperfine structure!

Zeeman effect
for a $s_{1/2}$ electron



Measure
bound positron spin-flip
frequency in high B

Calibrate B by measuring
Cyclotron frequency

f_s(*e spin-flip*) = 28.02.. GHz/tesla

Easier than $\bar{p}$ magnetic moment (Ulmer et al.),
Magnetic moment is ~600x larger

Ratio of spin-flip to cyclotron frequency

$$\frac{f_s}{f_c} = \left| \frac{\bar{g}_e(\bar{H}_2^-(v,0))}{2} \frac{q(e^+)}{m(e^+)} \frac{M(\bar{H}_2^-(v,0))}{q(\bar{H}_2^-)} \right|$$

Sensitive to $g(e^+)m(\bar{p})\,/m(e^+)$

CPT test #1

Even *N*, *N*≠0: add rotational HFS

$$E(v,N;M_S,M_N;B) \simeq E(v,N) - \bar{g}_e(v,N)B\bar{\mu}_B M_S + \bar{g}_r(v,N)B\bar{\mu}_B M_N + \bar{\gamma}(v,N)M_S M_N,$$

electron spin-rotation interaction

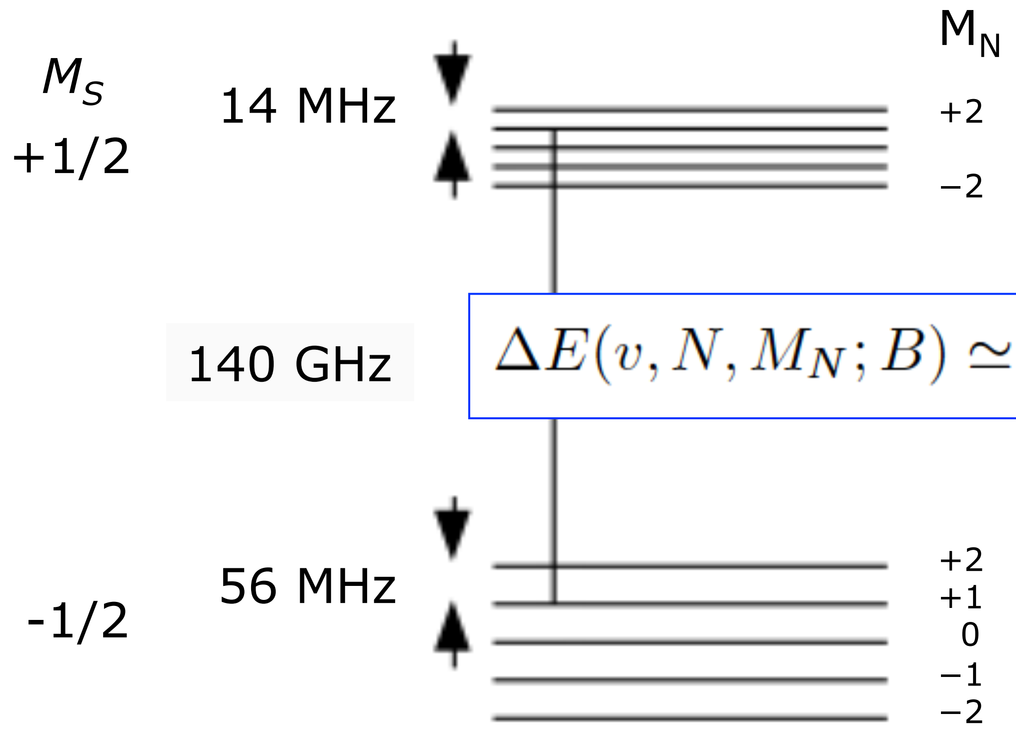
$\Delta M_S = \pm1,\ \Delta M_N = 0$ electron spin-flip transition

$$\Delta E(v,N,M_N;B) \simeq \bar{g}_e(v,N)B\bar{\mu}_B - \bar{\gamma}(v,N)M_N$$

Even N, $N \neq 0$: add rotational HFS

e.g. consider v=0, N = 2 B = 5 tesla

Zeeman splitting of N=2



$$\boxed{\Delta M_S = \pm 1,\ \Delta M_N = 0}$$

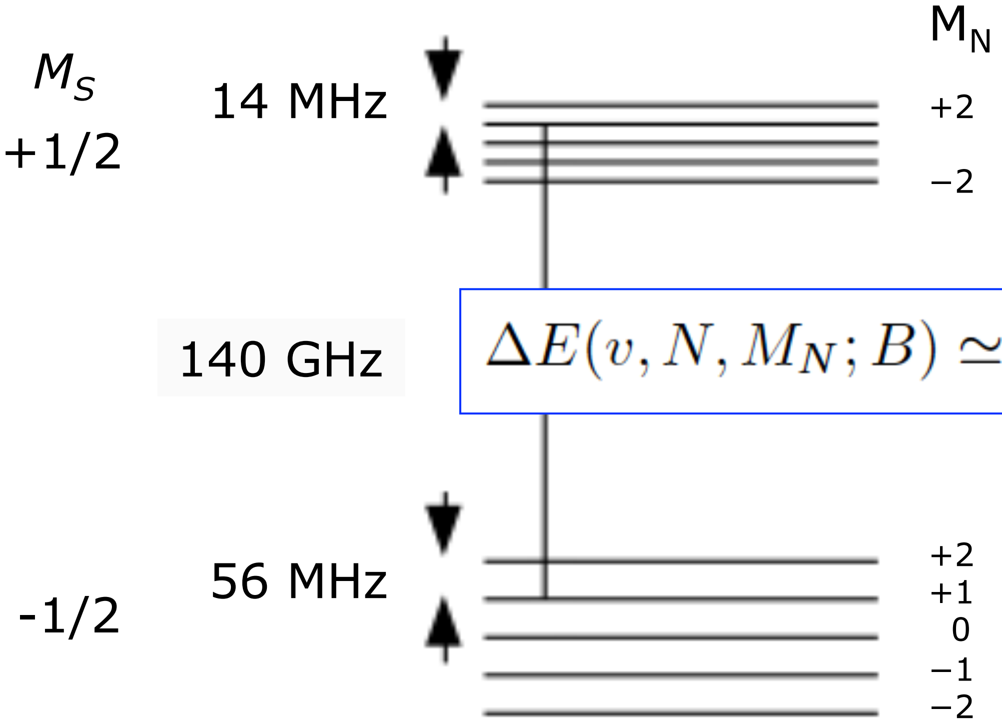
$$\boxed{\Delta E(v, N, M_N; B) \simeq \bar{g}_e(v, N) B \bar{\mu}_B - \bar{\gamma}(v, N) M_N}$$

Identifies M_N !

Even *N*, *N*≠0: add rotational HFS

e.g. consider v=0, N = 2　　B = 5 tesla

Zeeman splitting of *N*=2



$$\boxed{\Delta M_S = \pm 1,\ \Delta M_N = 0}$$

$$\boxed{\Delta E(v, N, M_N; B) \simeq \bar{g}_e(v,N) B \bar{\mu}_B - \bar{\gamma}(v,N) M_N}$$

Identifies M_N !

Identifies *v* and *N* !

Edmund Myers, LEAP 2018 Paris

Change in $e^{\pm}$ spin-flip freq. due to spin-rotation interaction identifies v, N !

$$\Delta E(v, N, M_N; B) \simeq \bar{g}_e(v, N) B \bar{\mu}_B - \bar{\gamma}(v, N) M_N$$

$$\begin{aligned} \Delta v &= 1, \qquad & \gamma(0,2) - \gamma(1,2) &= 2.950\ \text{MHz} \\ \Delta N &= 2, \qquad & \gamma(0,2) - \gamma(0,4) &= 0.868\ \text{MHz} \end{aligned}$$

few x 10^{-6} change to $e^{\pm}$ spin-flip frequency of ~140 GHz

Odd *N*, add nuclear spin HFS

I = *1*, 3x as many states …

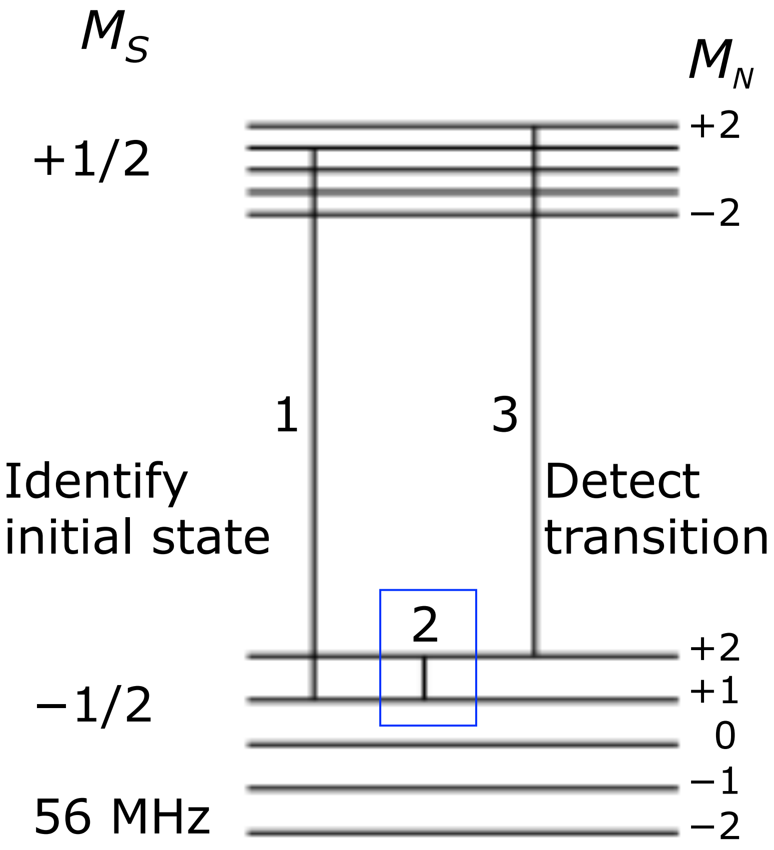
$$\boxed{\Delta M_S = \pm 1,\ \Delta M_N = 0,\ \Delta M_I = 0}$$

$$\boxed{\begin{aligned}\Delta E(v, N, M_N; B) \simeq \bar{g}_e(v, N) B \bar{\mu}_B \\ -\bar{\gamma}(v, N) M_N - \bar{b}(v, N) M_I + ..\end{aligned}}$$

Fermi-contact interaction

Triple resonance for HFS

Measure $\Delta M_N = \pm 1$ or $\Delta M_I = \pm 1$ transitions



Use $e^{\pm}$ spin-flip to identify initial and final states

Combinations of transitions separate Zeeman from Hyperfine

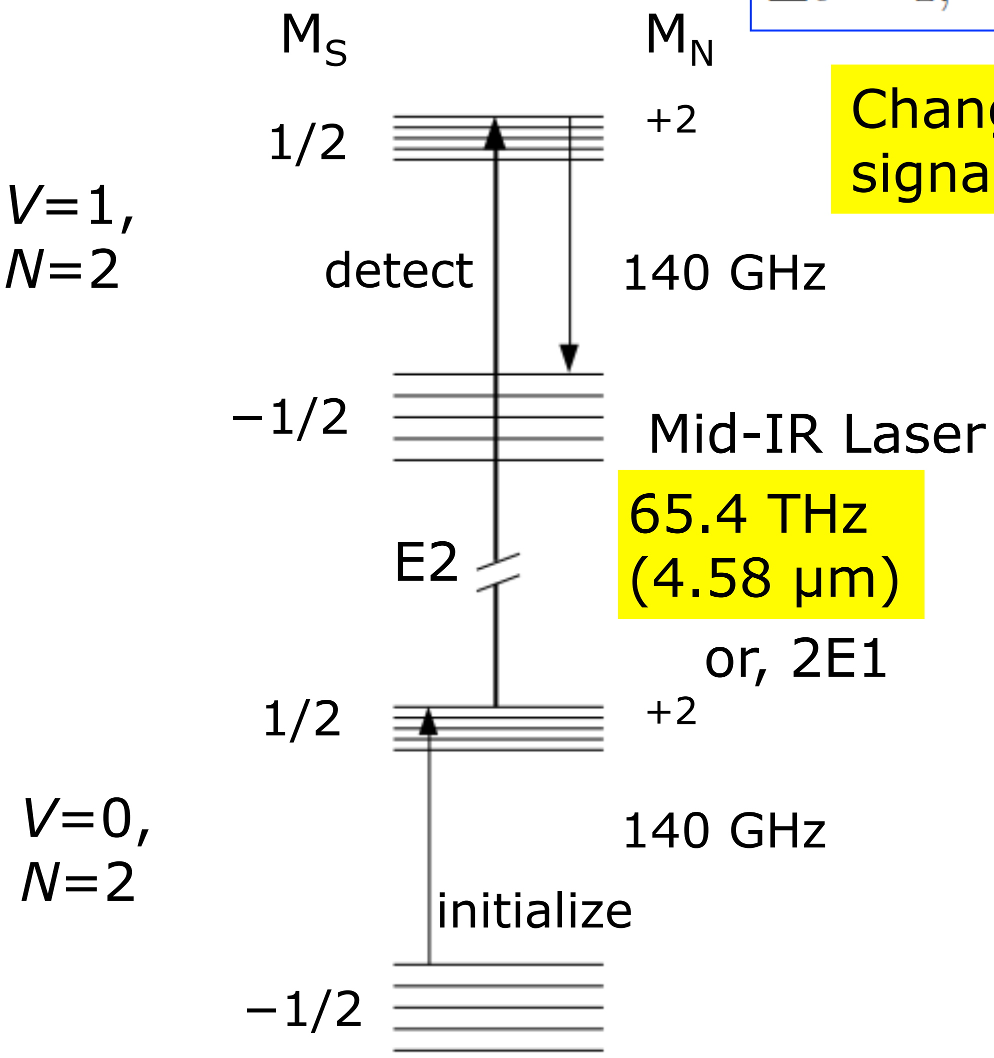
Zeeman: $\underline{\mu}_{\mathrm{R}}.\underline{B}$, $\underline{\mu}_{\mathrm{p}}.\underline{B}$ **like $\bar{p}$ *g*-factor**

HF: $\underline{\mu}_{\mathrm{p}}.\underline{\mu}_{\mathrm{e}}$ **like $\bar{\mathrm{H}}$ HFS**

CPT test #2

CPT Test #3: Vibrational Transitions

$$\Delta v = 1, \qquad \gamma(0,2) - \gamma(1,2) = 2.950\ \text{MHz}$$



M_S M_N

V=1, N=2

1/2 +2

detect

140 GHz

−1/2

Mid-IR Laser

65.4 THz (4.58 μm)

E2

or, 2E1

V=0, N=2

1/2 +2

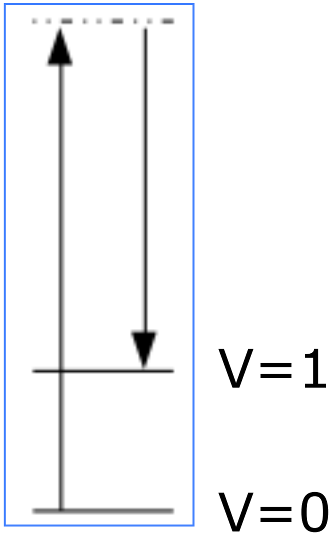
140 GHz

initialize

−1/2

Change in $e^{\pm}$ spin-flip frequency signals vibrational transition

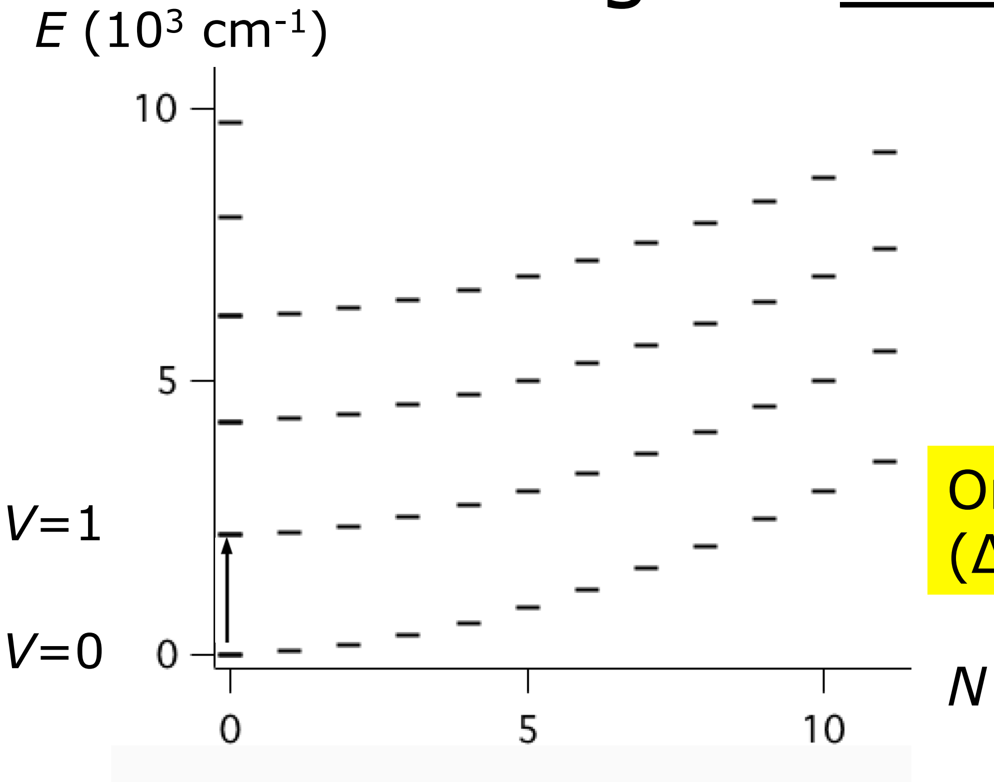
or, use Raman 2E1 transition and NIR lasers



V=1

V=0

Also detect vibrational transition using change in mass-energy



Works for N = 0

One vibrational quantum
$(\Delta E/c^2)/M(H_2^+) = 1.4 \times 10^{-10}$

See: Smith, Hamzeloui, Fink, Myers, PRL in press
Detect rotational energy change in H_3^+ from cyclotron frequency

$\bar{H}_2^-$ /H_2^+ Ro-Vibrational Spectroscopy $<10^{-16}$ in a *5 tesla Penning trap* !?

(N=2, "stretched to stretched") Zeeman shift = 7.5×10^5 Hz !

But, from cyclotron or *e* spin-flip, $\sigma(B)/B \ll 10^{-9}$

➔ $\sigma(f)/f < 10^{-17}$

Quadrupole shift ~ 25 Hz

Calibrate to ~10^{-6}, from characterization of trapping fields using ion's motional frequencies

➔ $\sigma(f)/f < 10^{-18}$

Zeeman Effect: Karr, Hilico et al

$\overline{H}_2^{-}/H_2^{+}$ Ro-Vibrational Spectroscopy $<10^{-16}$ in a *5 tesla Penning trap*?

If cool Axial (f_z = 1 MHz) and Cyclotron (f_c = 35 MHz) modes of ion **to 20 mK**;
Magnetron (f_m = 14 kHz) (by coupling to axial mode) to 0.3 mK

z_{rms} = 1.44 μm, r_c = 0.058 μm, r_m = 0.17 μm

Hence**, in Lamb-Dicke regime for transverse laser irradiation** at λ = 4.5 μm ➔ No 1st order Doppler shift

Second-order Doppler shift: 0.9×10^{-15}

How to cool:
Image current cooling, with dilution refrigerator
Electrical coupling to laser-cooled ion in another trap
Sympathetic cooling with laser-cooled –ve ion

How to make $\bar{H}_2^-$

$$\boxed{\bar{H}^+ + \bar{p} \rightarrow \bar{H}_2^- + e^+}$$

$\sigma = 6 \times 10^{-15}$ cm^2 at 0.01 eV
X. Urbain et al. J. Phys B (1986)

Inject $\bar{H}^+$ into $\bar{p}$ plasma, $n = 10^6$ cm^{-3}, $T = 100$K
$R = 1.4 \times 10^{-3}$ s^{-1} (~1/10 minutes)

$$\boxed{\bar{H}^+ + \bar{p} \rightarrow \bar{H} + \bar{H}}$$

$\sigma = 1.1 \times 10^{-12}$ cm^2 at 0.01 eV
M. Stenrup et al. PRA (2009)

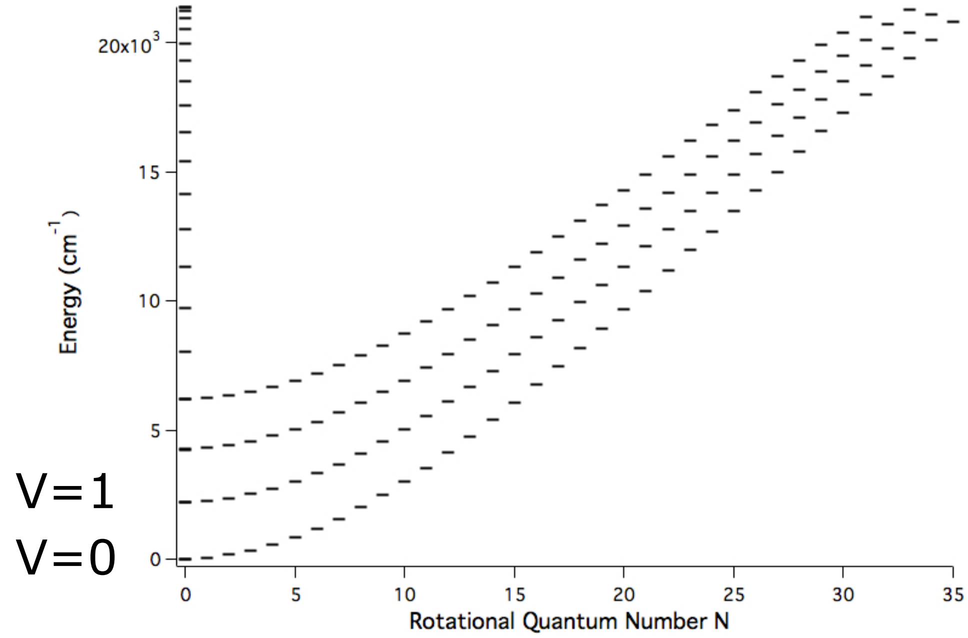
Hence, expect 1 $\bar{H}_2^-$ for every ~200 $\bar{H}^+$ injected

GBAR: 1 $\bar{H}^+$ every 2 minutes, so 1 $\bar{H}_2^-$ in ~ 6 hours

State Initialization: *v*, *N*

$$\bar{H}^+ + \bar{p} \rightarrow \bar{H}_2^-(v, N) + e^+$$

Expect *v* < 8, N < 10



Reduce *v:*
"Stark Quench"
(Induce E1 decay)

$\underline{E} = \underline{v} \times \underline{B} = (\underline{\omega} \times \underline{r}_c) \times \underline{B}$

$r_c = 4$ mm, $B = 10$ T

Reduce *N:*

Step-wise $\Delta v = \pm 1$, $\Delta N = -2$
E2 *v*= 0 ➔ *v*=1 ➔ *v*=0 ..

Things to do

Experimental development:

- H_2^+ e^- spin-flip detection
- H_2^+ precision spectroscopy in a Penning trap
- $\overline{H}_2^-$ making

Theory:

- Zeeman structure B = 0 - 10 T
- Stark quenching
- Raman transition rates
- $\overline{H}_2^-$ making

Things to do

Experimental development:

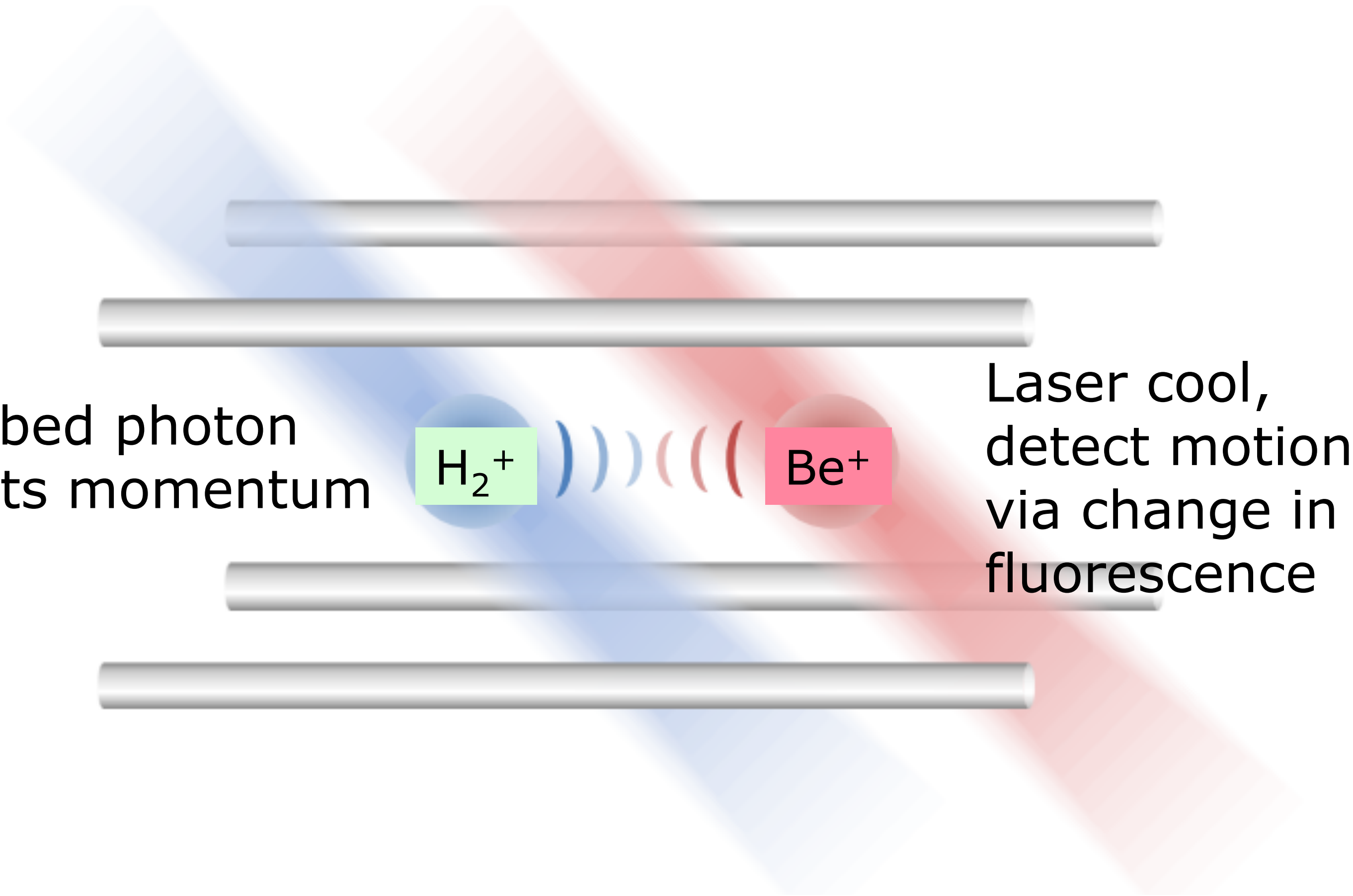
- H_2^+ e^- spin-flip detection
- H_2^+ precision spectroscopy in a Penning trap
- $\overline{H}_2^-$ making

Theory:

- Zeeman structure $B = 0 - 10$ T
- Stark quenching
- Raman transition rates
- $\overline{H}_2^-$ making

Thanks for your attention!

Quantum Logic Spectroscopy?



Absorbed photon
imparts momentum

Laser cool,
detect motional state
via change in
fluorescence

How to make $\bar{H}_2^-$

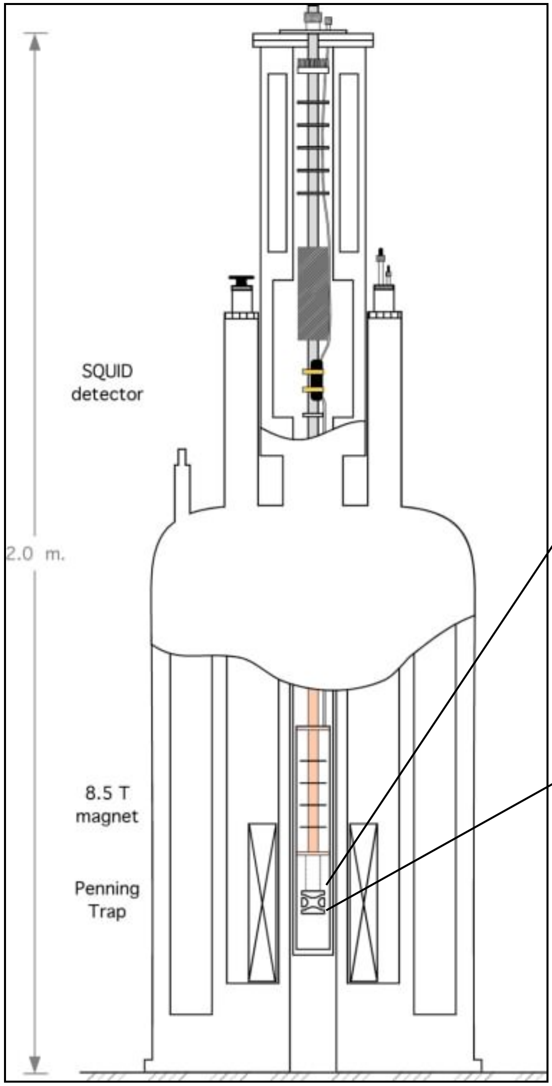
$$e^- + \bar{H}_2 \rightarrow \bar{H}_2^- + e^+ + e^- \ (\text{or } 2\gamma) \qquad (1)$$

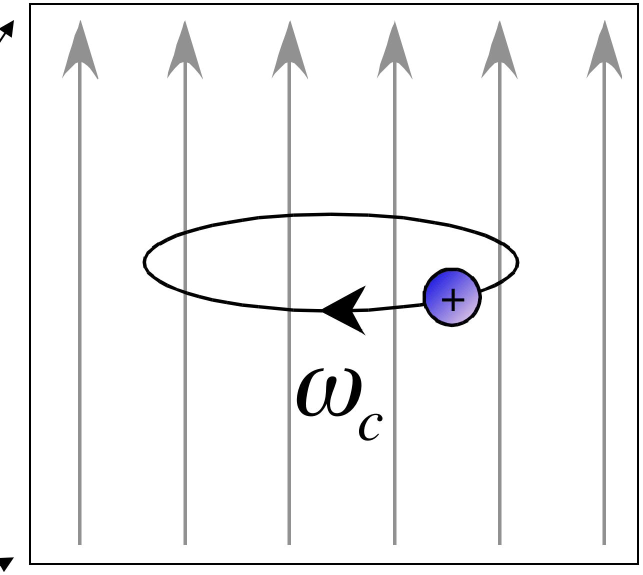
$$\bar{p} + \bar{H} \rightarrow \bar{H}_2^- + \gamma \qquad (2)$$

$$\bar{H}(1s) + \bar{H}(n \geq 2) \rightarrow \bar{H}_2^- + e^+ \qquad (3)$$

$$\bar{H}^+ + \bar{p} \rightarrow \bar{H}_2^- + e^+ \qquad (4)$$

Penning Trap: Cyclotron Frequency Ratio





$$\omega_c = \frac{B}{(m/q)}$$

$$R = \frac{\omega_{c0}}{\omega_{c1}} = \frac{q_0}{q_1}\frac{m_1}{m_0}$$

Testing CPT with $\bar{H}_2^-$: (with one ion in a Penning trap)

- Antihydrogen molecular ion has advantages compared to antiprotons and antihydrogen

- Use cryogenic Penning trap: measure cyclotron frequency and positron spin-flip frequency: gives $m(e^+)/m(\bar{p})$

- Positron spin-flip frequency can be used to identify state !!

- Hence, measure rotational and nuclear-spin Zeeman transitions, and also ro-vibrational transitions (non-destructively)

- Make $\bar{H}_2^-$ from $\bar{H}^+$ (Gbar)

Tests of CPT using anti-protons

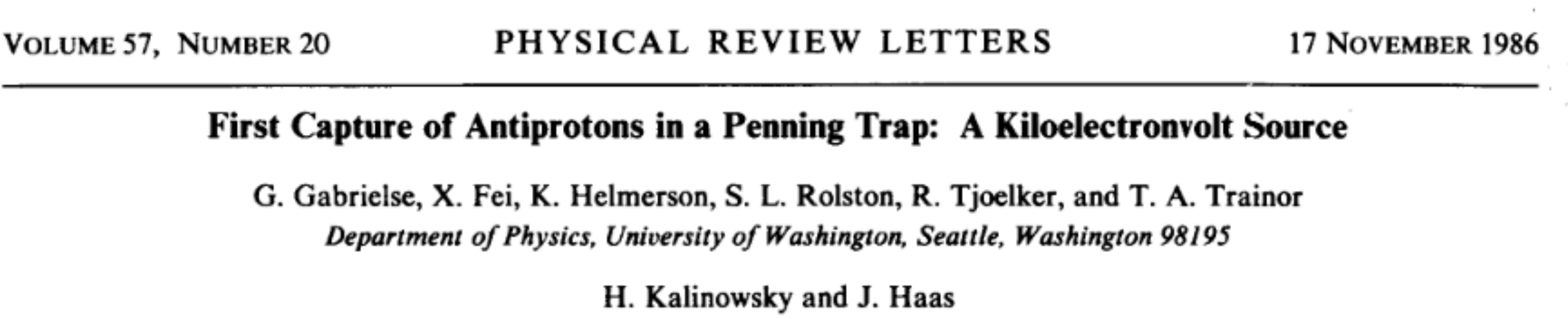
Compare mass and magnetic moments of p and $\bar{p}$ in a Penning trap

a) m/q is same to 9.0 x 10^{-11} (Harvard 1999)
6.9 x 10^{-11} (BASE 2015)

b) g_p is same to 1.5 x 10^{-9} (BASE 2017)

For proton, g_p measured to 3 x 10^{-10} (Mainz)

First trapping of anti-protons 1986



VOLUME 57, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

First Capture of Antiprotons in a Penning Trap: A Kiloelectronvolt Source

G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. Tjoelker, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

H. Kalinowsky and J. Haas

Gabrielse *et al*, (1999): p, $\bar{p}$ m/q same to 10^{-10}

Ulmer *et al*, (2017): p, $\bar{p}$ magnetic moment same to 10^{-9}

Trapping and manipulating single anti-ions in Penning traps is (now) relatively easy