THz-wave Electrometry Based on Lighshift Measurements with Cold Trapped HD^+ Ions

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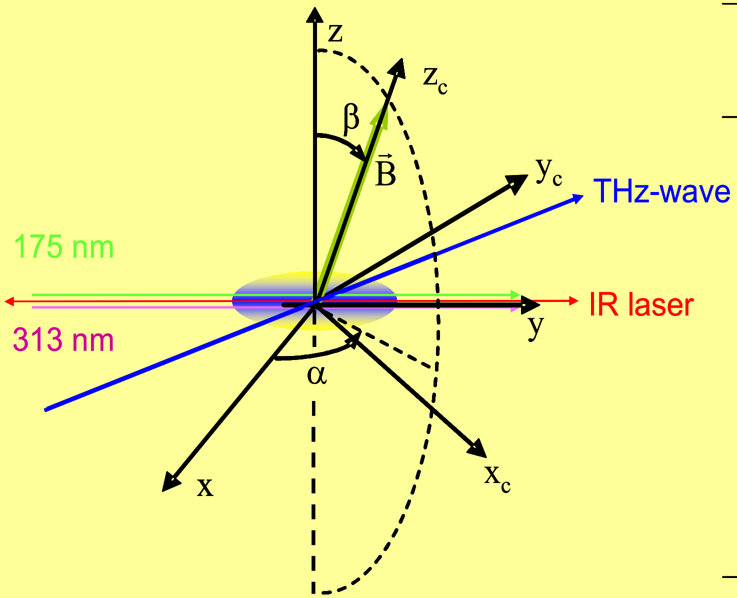
- Atom-based measurements : stability, reproducibility, SI-traceability

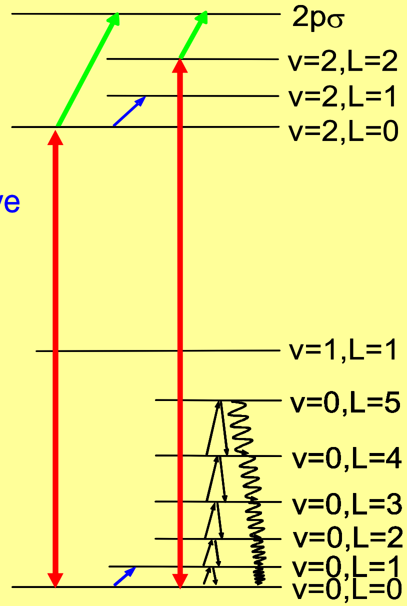
⇒ Weak microwave electric field detection at the µV/cm level; sensitivity limited by the photon shot noise

Nat. Phys. 8, 819 (2012); IEEE Trans. Antenna Propag. 62, 6169 (2014); Opt. Express 25, 8625 (2017)

- Comparison theory-spectroscopy with hydrogen molecular ions

Phys. Rev. Lett. 118, 233001 (2017); Phys. Rev. Lett. 97, 243001 (2006); J. Phys. B 44, 025003 (2011); Phys. Rev. A 89, 052521 (2014); Nature 581, 152 (2020); Science 369, 1238 (2020)





- Proposal to exploit systematic frequency shifts in two-photon rovibrational spectroscopy of cold trapped HD^+ ions
- Characterization of a magnetic field

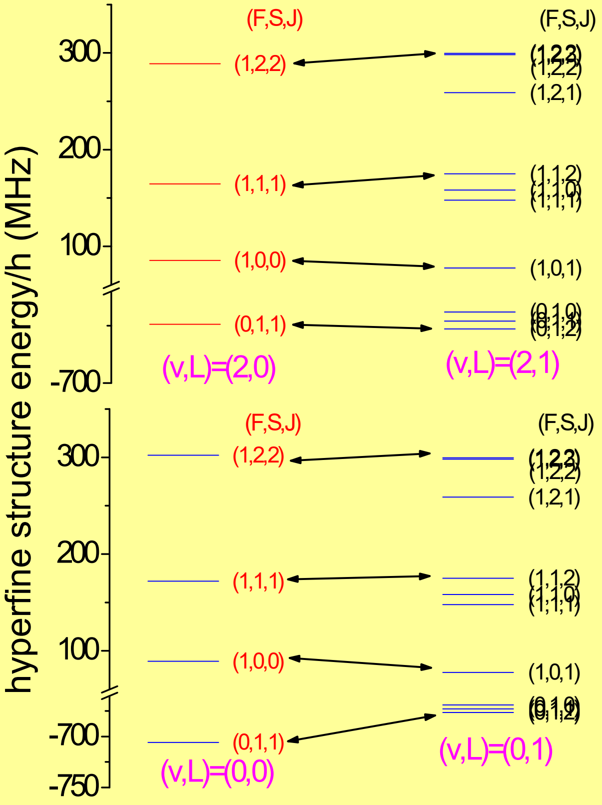
-Zeeman spectroscopy on (v,L)=(0,0)→(2,2)

- Characterization of a THz electric field

-probing lighshifts on (v,L)=(0,0)→(2,0)

Theoretical calculations of HD^+ energy levels in external fields

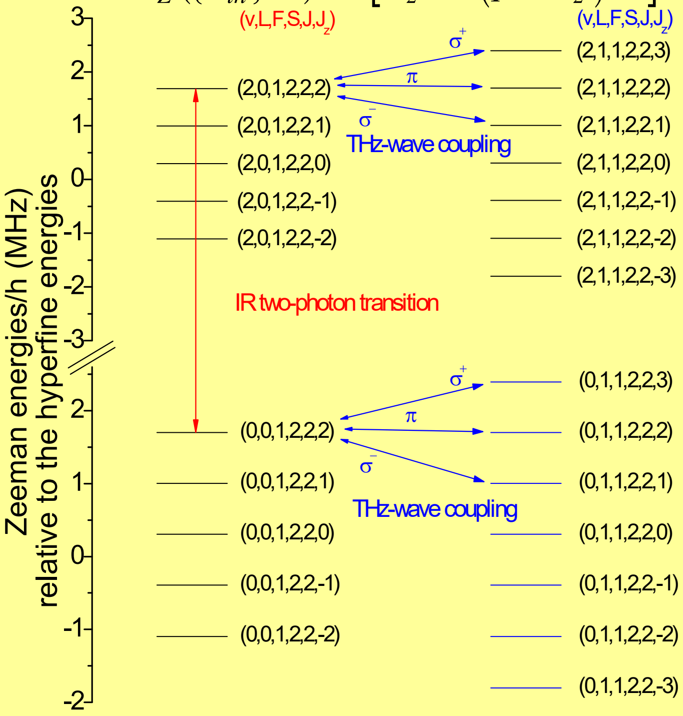
- Rovibrational energies : 10^{-12} precision
- Hyperfine splittings : 0.5 kHz accuracy
- Zeeman shifts of HD^+ energy levels : 10^{-4}-level precision for the Zeeman shift parameters
- Lighshifts of HD^+ energy levels : *standard dynamic polarizabilities of* HD^+



Mol. Phys. 78, 371 (1993)

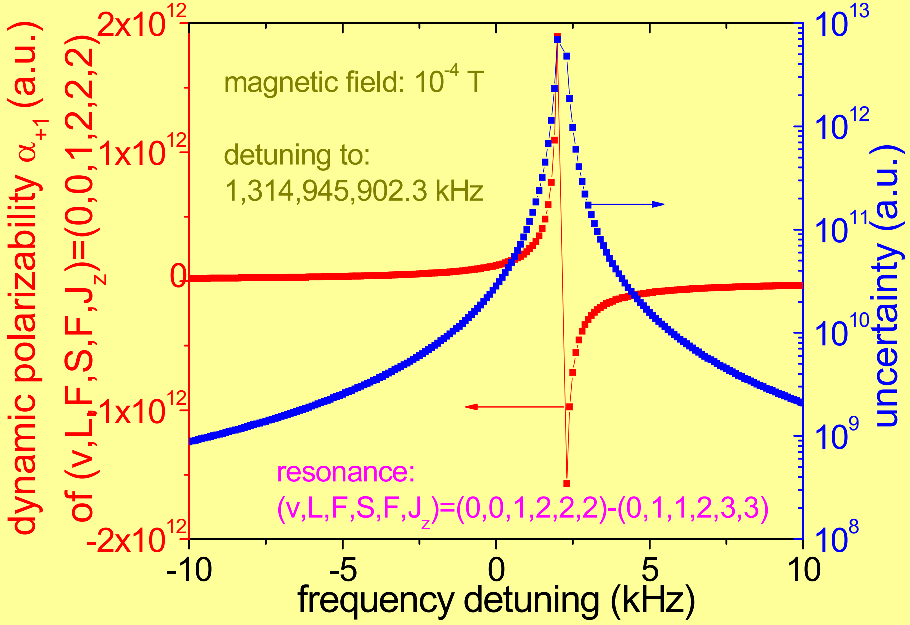
Phys. Rev. Lett. 97, 243001 (2006)

$$\Delta E_Z\left(\{U_{th}\};B\right)\approx h\left[tJ_zB+\left(q+rJ_z^2\right)B^2\right]$$



J. Phys. B 44, 025003 (2011)

$$\Delta E_{LS}=-\frac{1}{4}\sum_{q=\{-1,0,1\}}(-1)^q\left|E_{THz,-q}\right|^2\alpha_{n,q}\left(\{U_{th}\};q,B,f_{THz}\right)$$



Hyperfine Interact. 210, 25 (2012)

Phys. Rev. A 50, 2304 (1994)

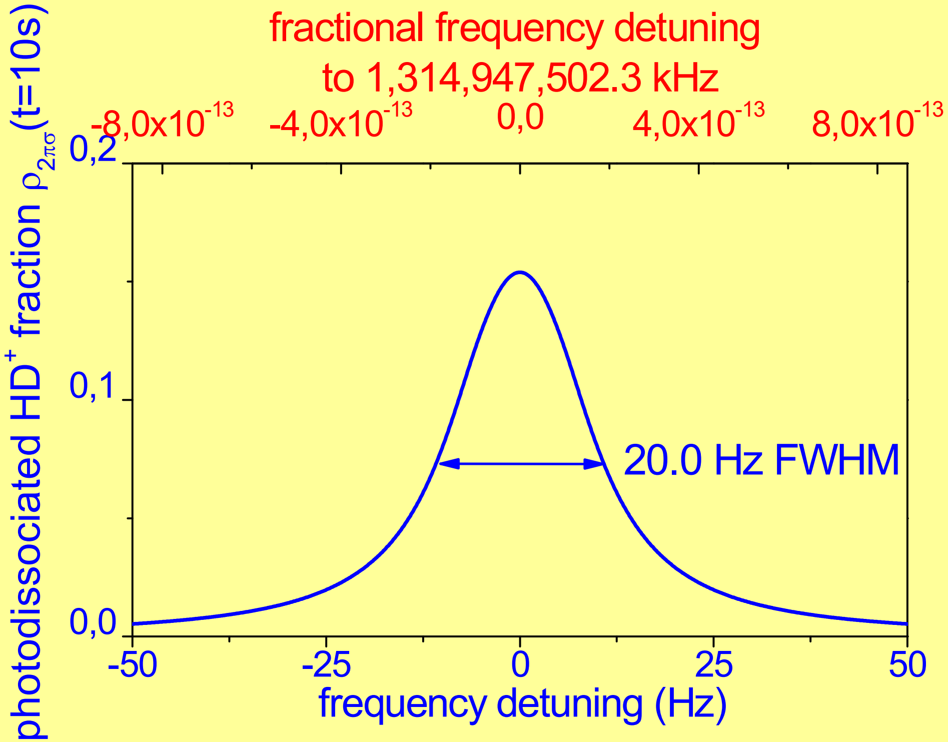
Two-photon spectroscopy of cold trapped HD^+

Accuracy and resolution

IEEE Trans. Instrum. Meas. 68, 2151 (2019)

- rate equation model for REMPD

Transition rates : $\Gamma_{2ph,v}$=10 s^{-1}; Γ_{diss}=200 s^{-1}
REMPD time : 10 s



- Allan variance at molecular ion QPN limit

⇒ 2-Hz uncertainty estimate in single-ion spectroscopy

Characterization of a magnetic field

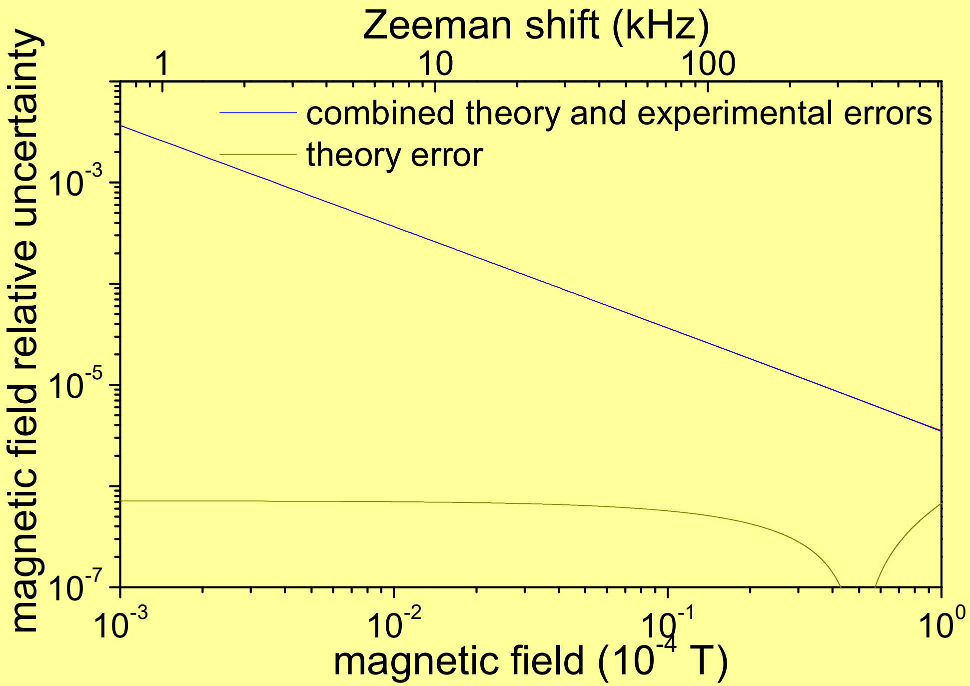
- probing a sensitive two-photon transition

(0,0,1,2,2,-2)→(2,2,1,2,4,0)

$$\Delta f_Z = \eta_B\left(\{U_{th}\}; J_z, J'_z\right)B + \eta_{B^2}\left(\{U_{th}\}; J_z, J'_z\right)B^2$$

- evaluation of exp./theor. uncertainties

δf_z=2 Hz; $\delta q=\delta r$=50 MHz/T^2; δt=5 kHz/T



⇒ detection of magnetic fields at the 10^{-10} T level

⇒ limit from theory errors in the 10^{-14}-10^{-11} T range

THz-wave characterization by two-photon spectroscopy of HD^+

Scalar THz electrometry

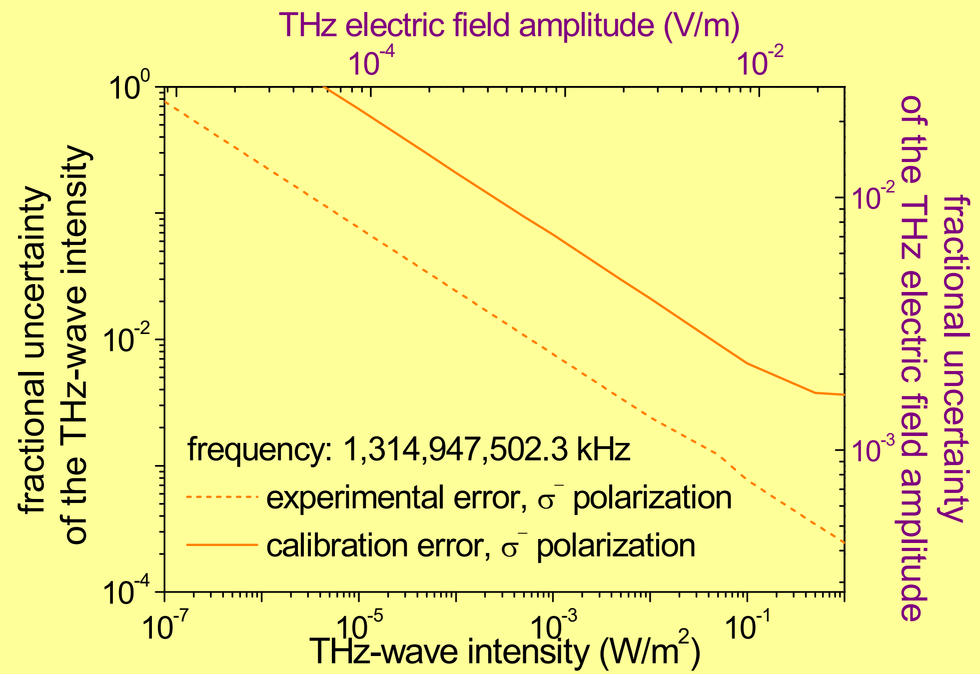
• probing a two-photon transition lightshift

(0,0,1,2,2,2)→(2,0,1,2,2,2)

$$\Delta f_{LS} = -\frac{\left|E_{THz}\right|^2}{8}\left(\alpha_{n'}\left(\{U_{th}\};B,f_{THz}\right)-\alpha_{n}\left(\{U_{th}\};B,f_{THz}\right)\right)$$

• evaluation of exp./theor. uncertainties

frequency measurement, magnetic field calibration and THz-wave frequency, theoretical parameters



⇒ detection of weak electric fields at the μV/m level

⇒ precision limit from theory errors at the 10^{-3} level

Vector THz electrometry

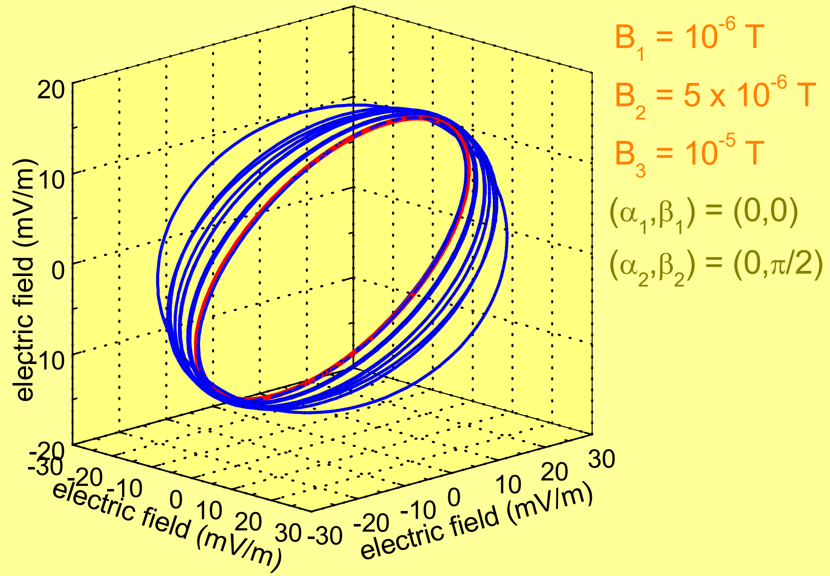
• probing six lightshifts for two orientations and three values of the magnetic field on

(0,0,1,2,2,2)→(2,0,1,2,2,2)

$$\Delta f_k^{(\alpha_i,\beta_i)} = \sum_q c_{\mathrm{F,q}}\cdot\Delta\alpha_{k,q}\left(\{U_{th}\};f_{\mathrm{THz}},B_k\right)\left|E_{THz,-q}\left(\alpha_i,\beta_i,E_x,E_y,E_z,\varphi_x,\varphi_y\right)\right|^2$$

• inversion of the nonsingular system

Reference THz-wave electric field ($E_x=E_y=E_z=15.83$ mV/m, $\phi_x=\pi/4$, $\phi_y=\pi/3$), frequency: 1,314,947,502.3 kHz



⇒ Retrieved THz-wave electric field ($E_x=15.88(92)$ mV/m, $E_y=15.74(72)$ mV/m, $E_z=15.831(3)$ mV/m, $\phi_x=0.78(6)$ rad, $\phi_y=1.05(1)$ rad)