

Motivation

Atom-based quantum technologies enable standards for the electromagnetic fields with improved sensitivity, stability, resolution and reproducibility. Rydberg atom spectroscopy provides self-calibrated measurements in the microwave domain [1]. Increase in frequency and development of multi-parameter quantum measurements, including phase and polarization state, are required for future quantum sensing applications. This contribution proposes to measure electromagnetic fields using precision spectroscopy with cold trapped HD⁺ ions. Calibration with traceability to the SI second and to the fundamental constants may be performed by comparing the measurements of the systematic frequency shifts induced on HD⁺ lines with the predictions of the quantum molecular theory [2].

Ab-initio HD⁺ energy levels and shifts in external fields

$$E(v, L, F, S, J, J_z) = E_{rv}(v, L) + E_{hf}(v, L, F, S, J) + \Delta E_Z(v, L, F, S, J, J_z; B) + \Delta E_{LS}(v, L, F, S, J, J_z; q, B, f_{THz})$$

-rovibrational energies:

• 10⁻¹²-level precision [3]

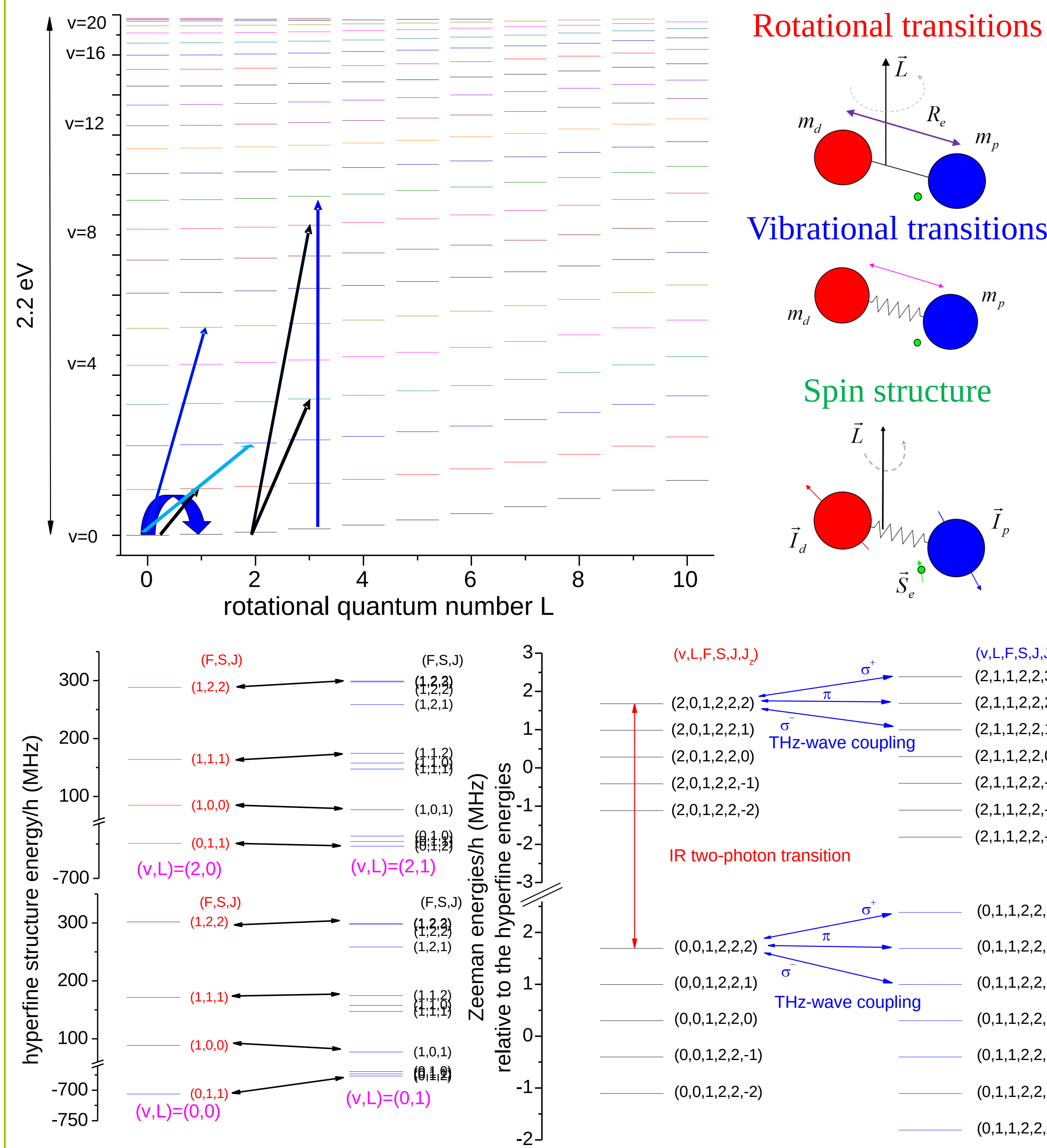
-hyperfine splittings:

• 0.5 kHz accuracy [4]

-magnetic level shift by Zeeman effect [5]:

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

10⁻⁴-level precision for t, q, r parameters

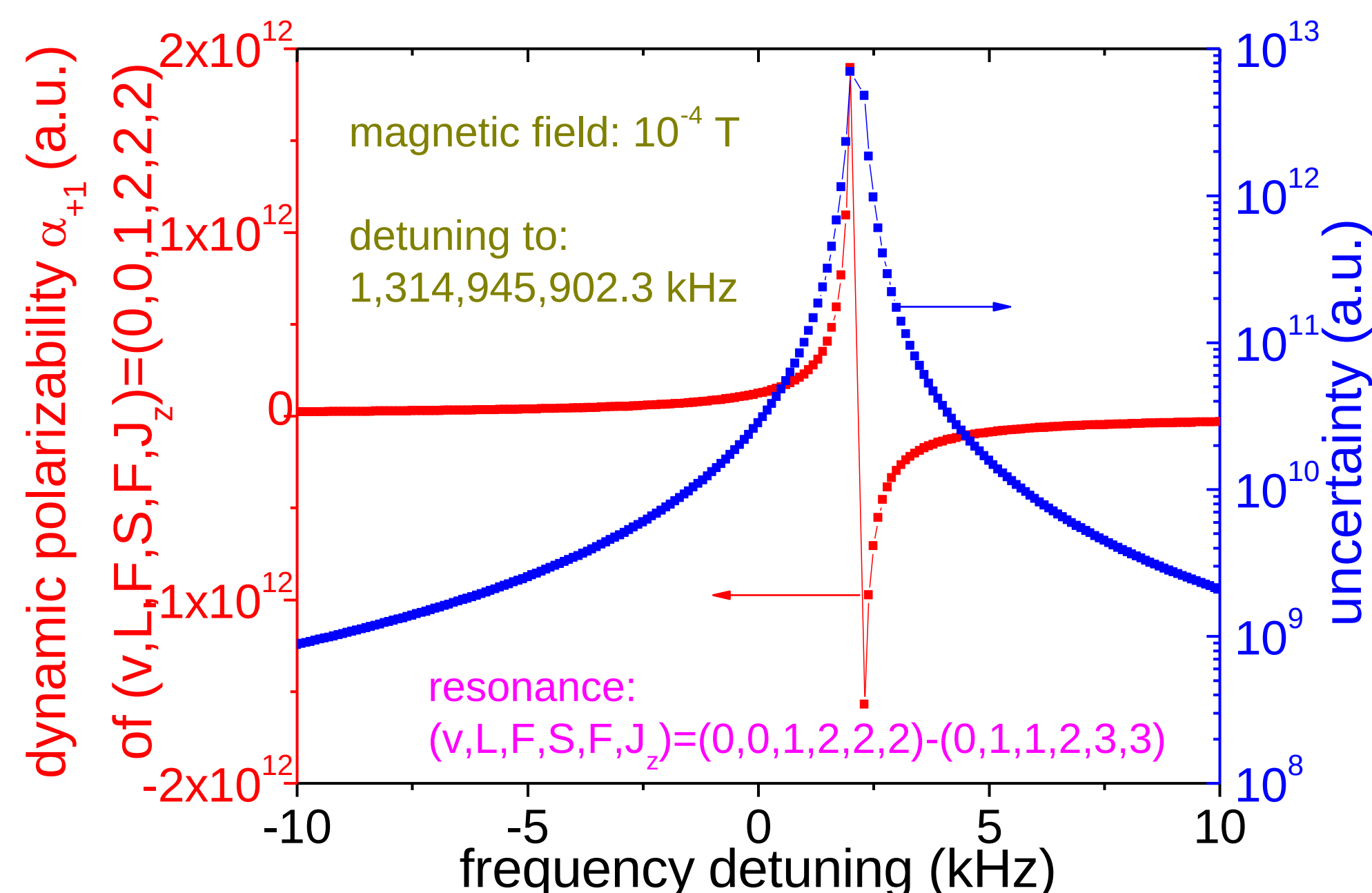


Lightshifts induced by a THz electric field are quantified with the standard components of the electric field and dynamic polarizabilities of HD⁺

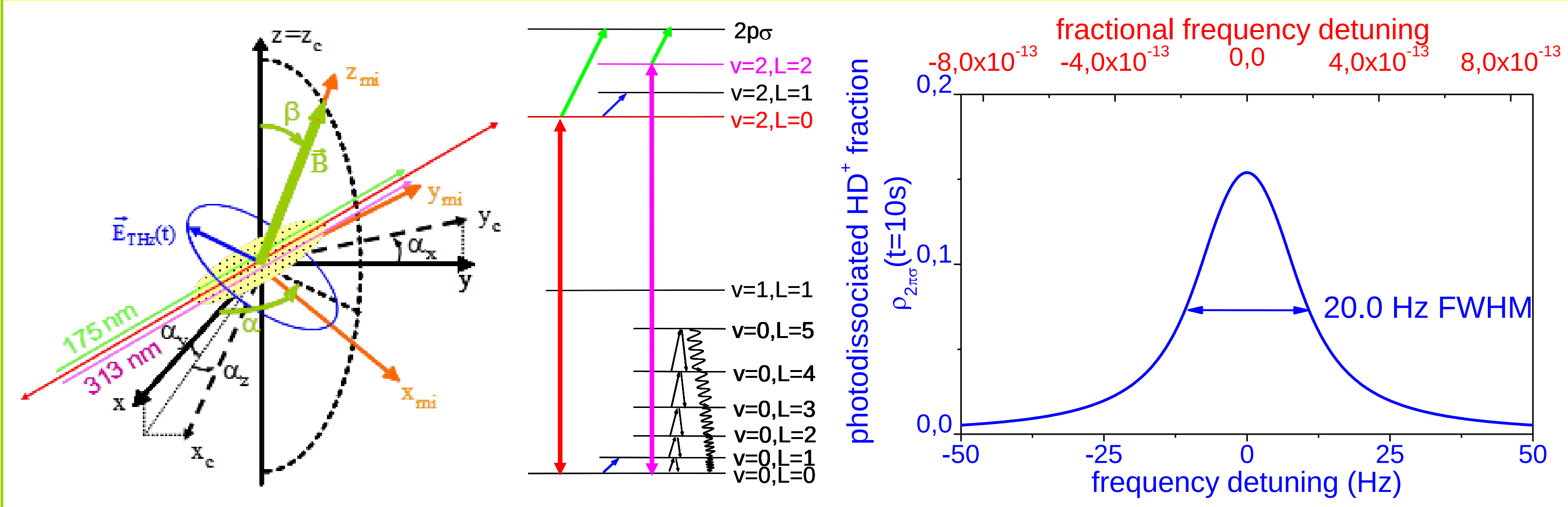
$$\Delta E_{LS}(n; |E_{THz}|) = -\frac{1}{4} |E_{THz}|^2 \sum_r \text{Re} \left[\frac{\langle n | (\vec{d} \cdot \hat{\epsilon})^+ | r \rangle \langle r | (\vec{d} \cdot \hat{\epsilon}) | n \rangle}{E_r - E_n - \hbar\omega - i\hbar \frac{\gamma_r + \gamma_n}{2}} + \frac{\langle n | (\vec{d} \cdot \hat{\epsilon}) | r \rangle \langle r | (\vec{d} \cdot \hat{\epsilon})^+ | n \rangle}{E_r - E_n + \hbar\omega + i\hbar \frac{\gamma_r + \gamma_n}{2}} \right]$$

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

Frequency dependence of a standard dynamic polarizability and its uncertainty is predicted with HD⁺ theory and experimental parameters [5-8]



Two-photon spectroscopy of cold trapped HD⁺



-Two-photon infrared spectroscopy of HD⁺ ions trapped and sympathetically cooled with 313 nm laser-cooled Be⁺ ions

-Detection by dissociation of (v,L)=(2,0) with 175-nm laser radiation

=> Limit of the fractional resolution beyond the 10⁻¹² level [9]

=> Frequency measurements with QPN-limited uncertainty rovibrational transition at ~2 Hz [9]

-Relate measurements in a slightly nonorthogonal reference frame $CCF(x_c, y_c, z_c)$ defined with three coil pairs to the ideal Cartesian laboratory frame $LCF(x, y, z)$ using an adjustable frame $MICF(x_{mi}, y_{mi}, z_{mi})$

1) Zeeman spectroscopy on (v,L)=(0,0)→(2,2) @ 57.701 THz

or (v,L)=(0,0)→(0,2) @ 1.968 THz

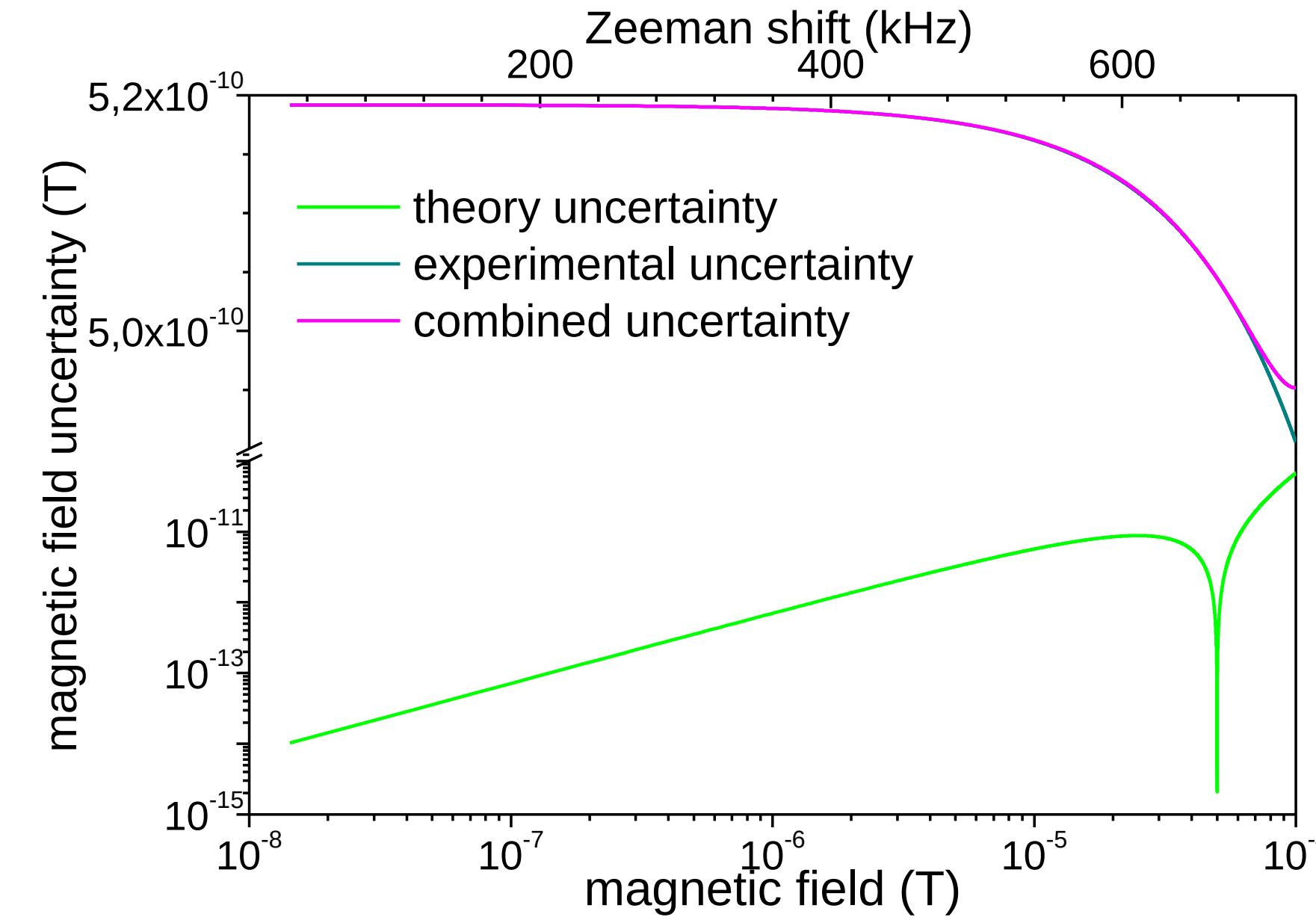
=> Magnetic field strength, orientation and the offset magnetic field

2) Lightshifts induced on (v,L)=(0,0)→(2,0) @ 55.909 THz by a THz-wave off-resonantly coupled to (v,L)=(0,0)→(0,1) @ 1.315 THz

=> Amplitudes and phases of the Cartesian components of the THz electric field

Magnetic field sensing by Zeeman spectroscopy

Zeeman shift measurements for hyperfine transitions (v,L,F,S,J,J_z)=(n,J_z)→(n',J'_z)

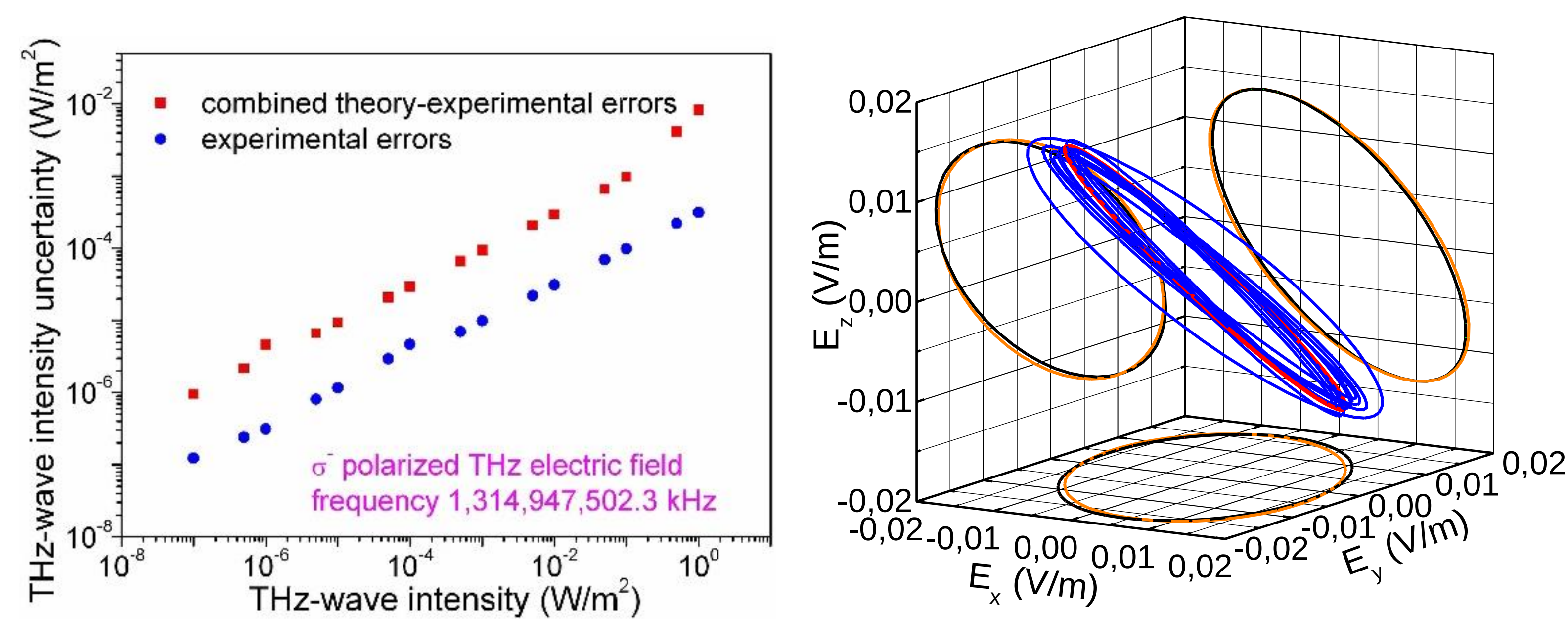


=> Absolute calibration of the magnetic field on (0,0,1,2,2,-2)→(2,2,1,2,4,0) transition

=> Sensitivity @ 10⁻¹⁰ T level & negligible theory error

THz electric field sensing

THz-wave sensing from lightshifts of the (0,0,1,2,2,2)→(2,0,1,2,2,2) transition



Sensitivity and precision in THz-wave detection: $\delta f_{LS}(E_{THz}) = -\frac{E_{THz}^2}{8} \Delta\alpha(\{U_{th}\}; B, f_{THz})$

THz electric field in the LCF: $\vec{E}_{THz}(t) = \sum_{j=\{x,y,z\}} \frac{E_j \vec{e}_j}{2} \times e^{-i(\omega t + \phi_j)} + c.c.$

Probe six lightshifts for two orientations and three values of the magnetic field:

$$\delta f_i(I_{1,i}, I_{2,i}, I_{3,i}) = -\frac{1}{4} \sum_{q=\{-1,0,1\}} (-1)^q |E_{THz,q}^{(\alpha_i, \beta_i)}|^2 \Delta\alpha_{i,-q}(\{U_j\}, \{\vec{B}\{V_k\}, I_{1,i}, I_{2,i}, I_{3,i}\}, f_{THz})$$

Transformation relations: $|E_{\sigma^-, \pi, \sigma^+}^{(\alpha, \beta)}|^2 = f_{\sigma^-, \pi, \sigma^+}(\alpha, \beta, E_x, E_y, E_z, \phi_x, \phi_y)$

Inversion of a nonsingular system of equations:

=> 5 traceable parameters for a circularly polarized THz electric field in the LCF frame
=> uncertainties for amplitudes at <mV/m level, and for phases at the 0.1 mrad level

References

[1] S.A. Sedlacek et al, Nat. Phys. 8, 819 (2012)

[2] F.L. Constantin, Atoms 8, 70 (2020)

[3] V.I. Korobov et al, Phys. Rev. Lett. 118, 233001 (2017)

[4] D. Bakalov et al, Phys. Rev. Lett. 97, 243001 (2006)

[5] D. Bakalov et al, J. Phys. B 44, 025003 (2011)

[6] R.E. Moss, Mol. Phys. 78, 371 (1993)

[7] D. Bakalov, S. Schiller, Hf. Interact. 210, 25 (2012)

[8] Z. Amitay et al, Phys. Rev. A 50, 2304 (1994)

[9] F.L. Constantin, IEEE TIM 68, 2151 (2019)