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Characterization of a THz Electric Field using Precision Spectroscopy of Molecular Ions

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Abstract: SI-traceable calibration of the amplitudes and phases of the Cartesian components of a THz electric field may be performed by comparing measurements of the lighshifts of HD^+ two-photon rovibrational transitions with molecular ion theory predictions.

1. Introduction

The atomic spectroscopy was exploited to provide SI-traceable measurements, sub-wavelength resolution, accurate, stable and long-term reproducible detection of microwave electric fields [1]. The spectroscopy of the Rydberg states of the alkali metals was exploited to detect weak electric fields at the μV/cm level with a sensitivity limited by the photon shot noise [2]. The precision of the measurements of the HD^+ transitions was significantly improved recently, reaching a fractional uncertainty of 1.3×10^{-11} for the fundamental rotational transition [3], and 2.9×10^{-12} for a two-photon rovibrational transition [4]. The ab-initio calculations provided accurate predictions for the HD^+ energy levels [5,6] and their shifts in external fields [7,8]. The two-photon spectroscopy of HD^+ has the potential to improve the fractional resolution and accuracy at the 10^{-12} level or better [9]. This contribution proposes to exploit the sensitivity of a two-photon rovibrational transition of HD^+ to external fields in order to detect a THz-wave that is off-resonantly coupled to the HD^+ energy levels. The amplitude of the THz electric field may be calibrated subsequently by comparing the measurement of the induced frequency shift and the prediction of the molecular ion theory. A set of independent lightshift measurements can be converted into the amplitudes and the phases of the Cartesian components of the electric field of the THz-wave.

2. Results

The measurements may be performed with the experimental setups with HD^+ ions trapped and sympathetically cooled with laser-cooled Be^+ ions [3,4]. The HD^+ transitions addressed in the sensing scheme are indicated in Fig. 1.(a). The measurements address the $(v,L,F,S,J,J_z)=(0,0,1,2,2,2)\rightarrow(2,0,1,2,2,2)$ Zeeman component of the two-photon transition of HD^+ at 55.909 THz (the energy levels are labelled with the quantum numbers for the HD^+ spin coupling scheme [6]). The detection of this transition may be performed by dissociation of the $(v,L)=(2,0)$ level with a 175 nm laser [9].The experimental uncertainty of the frequency of the two-photon transition is estimated at 2.49 Hz, using the quantum projection noise limit in a single-ion spectroscopy experiment. A THz-wave slightly detuned to the Zeeman subcomponents of the $(v,L)=(0,0)\rightarrow(0,1)$ rotational transition at 1.315 THz, or $(v,L)=(2,0)\rightarrow(2,1)$ at 1.197 THz, may be detected by measuring the lightshift induced on the two-photon transition.

A static magnetic field is applied on the ion trap using three coil pairs oriented orthogonally along the axes of the Cartesian laboratory frame. The magnetic field is exploited to define the quantisation axis and to tune the HD^+ energy levels. The magnetic field magnitude may be calibrated by comparing measurements by Zeeman spectroscopy of the $(v,L,F,S,J,J_z)=(0,0,1,2,2,-2)\rightarrow(2,2,1,2,4,0)$ two-photon transition of HD^+ with the predictions of the ab-initio theory. The uncertainty for magnetic fields smaller than 10^{-4} T is estimated at the 4×10^{-10} T level, limited by the experimental uncertainty of the frequency of the two-photon transition.

The AC-Stark shifts induced by a THz-wave are quantified with the dynamic polarizabilities of the HD^+ energy levels. They are calculated with their uncertainties using the second-order perturbation theory in function of a set of theoretical parameters (the HD^+ energy levels, the rotational transition dipole moments, the radiative linewidths of the HD^+ energy levels) and experimental parameters (the magnitude of the magnetic field, the polarization and the frequency of the THz-wave). The polarizability of a Zeeman level displays narrow dispersion-like resonances where the uncertainty increases at the frequencies of the electric dipole-allowed couplings to others levels (Fig. 1.(b)).

The performances of sensitivity and precision of the THz electric field measurements are evaluated by translating the uncertainties from the frequency measurements and from the ab-initio calculations of the theoretical parameters. For example, the measurement of the lightshift of the $(v,L,F,S,J,J_z)=(0,0,1,2,2,2)\rightarrow(2,0,1,2,2,2)$ transition may be exploited to detect an electric field as low as 6 μV/m of a THz-wave at 1,314,947,502.3 kHz with π polarization, by optimizing the value of the magnetic field in the ion trap. This result corresponds to a thirty times improvement comparing to the value of the weakest microwave electric field detected with the Rydberg atom spectroscopy method [2]. In addition, the precision of the calibration of the THz-wave with an intensity of 1 W/m^2 based on lightshift measurements is at the 10^{-3} level and is limited by the accuracy of the dynamic polarizability calculation.

The polarization ellipse (PE) of a THz electric field in three dimensions, described in the Cartesian laboratory frame with three real positive amplitudes and two phases $(E_x,E_y,E_z,\phi_x,\phi_y)$, may be fully characterized using lightshift measurements. Let's consider a reference THz-wave with a frequency of 1,314,947,502.3 kHz, an intensity of 1 W/m^2, σ^+ polarization, and propagating along a direction defined with Euler angles $(\alpha,\beta)=(\pi/4,\pi/4)$ in the laboratory frame. The PE of the THz-wave may be determined from a set of six independent lightshift measurements for the $(v,L,F,S,J,J_z)= (0,0,1,2,2,2)\rightarrow(2,0,1,2,2,2)$ transition for three magnetic fields $B_1 = 10^{-6}$ T, $B_2 = 5 \times 10^{-6}$ T, $B_3 = 10^{-5}$ T and two orientations defined with the Euler angles $(\alpha,\beta) = (0,0)$ and $(\alpha,\beta) = (0,\pi/2)$. The lightshifts are simulated by adding to the theoretical values for the reference THz-wave a Gaussian noise with zero mean frequency and standard deviation given by the assumed uncertainty of the HD^+ frequency measurements. The squared standard components of the THz electric field with respect to the two orientations of the quantization axis are subsequently derived using the differential dynamic polarizabilities of the two-photon transitions, evaluated as the theoretical value plus a random Gaussian noise with zero mean and standard deviation given by the calculation uncertainty. Then, the parameters of the THz electric field in the laboratory frame may be determined analytically from the calculated values of the squared standard components.The polarization ellipses of the THz electric field in the laboratory frame retrieved from 10 sets of lightshift measurements are represented in Fig. 1.(c). The uncertainties are at the ($\delta E_x = \delta E_y = 1$ mV/m, $\delta E_z = 10$ μV/m, $\delta\phi_x = 0.1$ rad, $\delta\phi_y = 0.1$ rad) levels.

3. References

[1] H. Fan *et al.*, "Atom based RF electric field sensing," J. Phys. B **48**, 202001 (2015).

[2] S. Kumar *et al.*, "Rydberg-atom based radio-frequency electrometry using frequency modulation spectroscopy in room temperature vapour cells," Opt. Express **25**, 8625 (2017).

[3] S. Alighanbari, G.S. Giri, F.L. Constantin, V. Korobov and S. Schiller, "Precise test of quantum electrodynamics and determination of fundamental constants with HD^+ ions," Nature **581**, 152–158 (2020).

[4] S. Patra *et al.*, "Proton-electron mass ratio from laser spectroscopy of HD^+ at the part-per-trillion level," Science **369**, 1238–1241 (2020).

[5] V.I. Korobov, L. Hilico and J.-P. Karr, "Fundamental transitions and ionization energies of the hydrogen molecular ions with few ppt uncertainty," Phys. Rev. Lett. **118**, 233001 (2017).

[6] D. Bakalov, V.I. Korobov and S. Schiller, "High-precision calculation of the hyperfine structure of the HD^+ ion," Phys. Rev. Lett. **97**, 243001 (2006).

[7] S. Schiller *et al*, "Static and dynamic polarizability and the Stark and blackbody-radiation frequency shifts of the molecular hydrogen ions H_2^+, HD^+, and D_2^+," Phys. Rev. A **89**, 052521 (2014).

[8] D. Bakalov, V.I. Korobov and S. Schiller, "Magnetic field effects in the transitions of the HD^+ molecular ion and precision spectroscopy," J. Phys. B **44**, 025003 (2011).

[9] F.L. Constantin, "Double-resonance two-photon spectroscopy of hydrogen molecular ions for improved determination of fundamental constants," IEEE Trans. Instrum. Meas. **68**, 2151-2159 (2019).

Figure caption

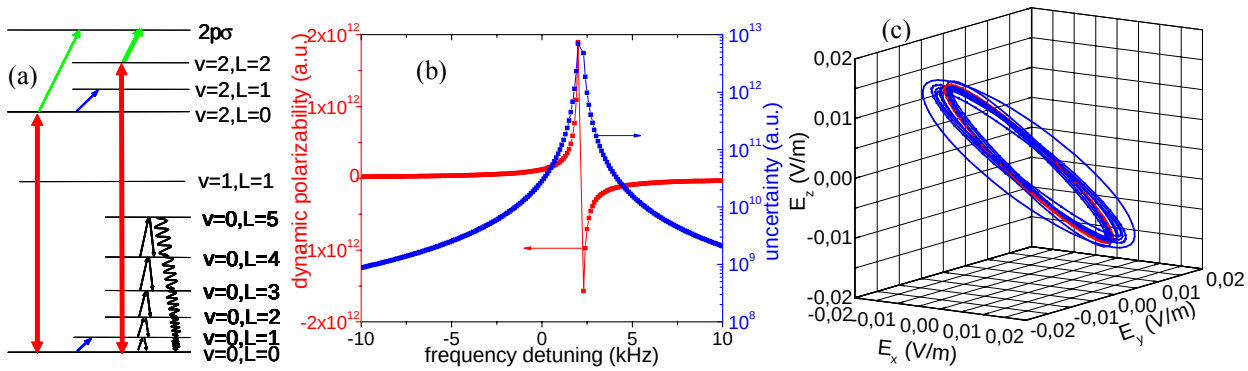

Fig. 1. (a) HD^+ transitions for THz-wave and magnetic field sensing : two photon infrared transitions (red lines), dissociation (green lines), blackbody radiation driven transitions (black lines), THz-wave driven dipole couplings (blue lines). (b) Frequency dependence of a term in the dynamic polarizability of the (v,L,F,S,J,J_z)= (0,0,1,2,2,2) level (red curve, left axis) and its uncertainty (blue curve, right-axis). This term characterizes in the lighshift induced by a σ^+-polarized THz-wave. Detuning to 1314945902.3 kHz. Magnetic field 10^{-4} T. (c) The reference polarization ellipse of the THz-wave (red curve). The polarization ellipses determined from lightshift measurements (blue curve).