Calibration of Electromagnetic Fields in Three Dimensions by Precision Spectroscopy of Hydrogen Molecular Ions

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Abstract

The electromagnetic fields may be characterized with high stability and accuracy by addressing quantum objects under strict control of their internal and external degrees of freedom. Quantum theory predicted accurately the hydrogen molecular ions energy levels and their shifts in external fields [1-4]. Recently, Doppler-free spectroscopy of cold trapped HD+ ions allowed significant improvements in accuracy and resolution [5-7]. This contribution proposes a new method to characterize electromagnetic fields in three dimensions with respect to a Cartesian laboratory reference frame by comparing the measurements of the systematic frequency shifts induced on two-photon transitions of HD+ with the quantum theory predictions.
The proposal is based on experimental setups using HD+ ions trapped and sympathetically cooled with laser-cooled Be+ ions [5-7]. Double resonance two-photon spectroscopy may be used to probe conjointly Zeeman components of the (v,L)=(0,0)→(0,2) and (v,L)=(0,0)→(2,0) transitions of HD+ [8]. These HD+ transitions may be measured with uncertainties estimated using the limit for the molecular ion quantum projection noise at _˜71 mHz and _˜2 Hz, respectively.

The comparison of Zeeman spectroscopy measurements of the (v,L,F,S,J,Jz)=(0,0,1,2,2,-2)→(0,2,1,2,4,0) rotational transition of HD+ with the quantum theory predictions are exploited to characterize the relative orientation of the coils that generate the magnetic field in the ion trap, the coil-to-field parameters, and the offset magnetic field. The orientation and the strength of a magnetic field of 10ˆ(-4) T applied to the ion trap may be calibrated with uncertainties estimated at the mrad level and the 10ˆ(-7) T level or better.

The measurements of the (v,L,F,S,J,Jz)=(0,0,1,2,2,2)→(2,0,1,2,2,2) rovibrational transition lightshifts are exploited further for the detection and the calibration of the electric field of a linearily polarized THz-wave that is slightly detuned to the (v,L,F,S,J)=(0,0,1,2,2)→(0,1,1,2,3) hyperfine transition of HD+. Upon optimisation of the strength of the magnetic field in the ion trap, this approach enables detection of a THz-wave with an amplitude as low as 6 μV/m. That corresponds to an improvement of thirty times comparing to the performances of the Rydberg atom spectroscopy method [9]. In addition, the comparison of the light-shift measurement with the theoretical prediction allows the calibration of the THz electric field amplitude with an accuracy at the level of 10 μV/m. Moreover, the amplitudes and

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the phases of the Cartesian components of the THz electric field may be derived from six lightshift measurements performed for three calibrated values of the magnetic field and two orientations. For a THz-wave with an intensity of 1 W/mˆ2, the amplitudes of the Cartesian components of the electric field may be characterized with μV/m-level uncertainties or better and the phases with mrad level uncertainties or better [10].

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