Atomic clock based on magneto-dipole transitions in highly charged ions

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A novel class of ultra-precise atomic clocks based on highly charged ions (HCI) was recently proposed[1]. In that paper, the authors studied highly-forbidden laser-accessible transitions within the $4f^{12}$ ground-state configurations of HCI. Their evaluation of systematic uncertainties demonstrated that such transitions may be used for building exceptionally accurate atomic clocks which may compete in accuracy with proposed nuclear clocks[2].

Here we evaluate the possibility of using magnetic dipole (M1) optical transitions in HCI, which are not as narrow as the E2 transition of Ref.[1] or ${}^1S_0 \rightarrow {}^3P_0$ transition used in the modern clocks. However, requiring the extremely narrow natural linewidth (<10 mHz) for strongly forbidden clock transitions holds no significance in the metrological practice, as the probed resonances are field-broadened anyways (at the level of 1-10 Hz)[3]. Therefore, here we propose employ the M1 optical transitions with wavelength $\lambda_{clock} \geq 1$ μm, with the natural linewidths being at the hertz or sub-hertz level.

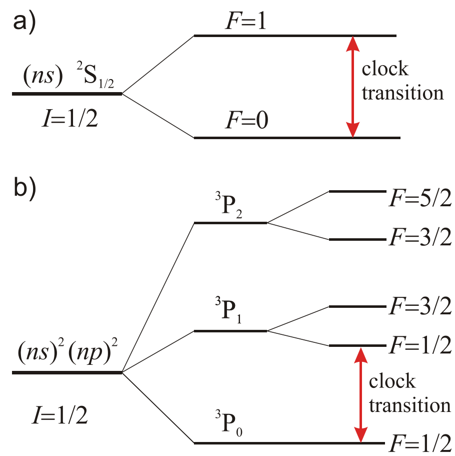

Fig. 1: Examples of M1 transitions in the case of nuclear spin I=1/2: a) Hyperfine clock transition in hydrogen-like ions; b) Fine-structure clock transition with suppressed electric-quadrupole shift in the case of two *p*-shell electrons.

We focus on two classes of such laser-accessible M1 transitions in HCI: within (i) hyperfine and (ii) fine-structure manifolds attached to the HCI ground states. First, the hyper-fine transition in hydrogen-like (or alkali-like) ions (Fig.1a). In particular, for stable isotopes with nuclear spin I=1/2 this transition in hydrogen-like ions can lie in the optical 0.5-3 μm region if $Z_i \geq 70$ (Z_i is the residual ion charge). As to the fine-structure manifolds, we find multiple HCIs with fine-structure M1 laser-accessible transitions. The constraint on Z_i depends on the balance between the total number of electrons and the nuclear charge. For example, for Al-like ions, $20 < Z_i < 30$. We identified clock transitions which are insensitive to quadrupole shifts (as an example, see Fig.1b, where quadrupole moment of clock states simply vanish).

Our analysis demonstrates that the atomic clocks based on the optical M1 transitions in HCIs can have very small *inherent* uncertainties (at the fractional level below 10^{-20}-10^{-21}) for the dominant systematic shifts (such as BBR, electric-quadrupole, Zeeman and AC-Stark shifts). Moreover, by contrast to the conventional atomic clock based on neutral atoms or singly (weakly) charged ions such HCI clocks are exceptionally sensitive to hypothetical drifts of fundamental constants.

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