

Atomic clocks and search for variation of the fine structure constant

V. A. Dzuba, and V. V. Flambaum

School of Physics, University of New South Wales, Sydney 2052, Australia

Tel +61-2-93855682, Fax +61-2-93856060

E-mail: dzuba@unsw.edu.au

Possible variations of the fundamental physical constants are suggested by unified theories, such as string theory and M theory (see, e.g. [1]). A number of works have been done in the last few years in an attempt to find experimental evidence of any space-time variation of the fine structure constant α . The search goes mostly in two ways. One is based on analysis of the absorption spectra of distant quasars. Comparing the spectra of atoms or ions in distant gas clouds which intersect the sight lines towards the quasars with the laboratory spectra allows one to put bounds on the space-time variation of α . Another way uses precise atomic clocks in laboratory measurements. Different atomic transitions depend differently on the fine structure constant. Comparing the rates of different atomic clocks over long periods of time allows one to put bounds on the local change of α with time.

The strongest laboratory limit on the time variation of α was obtained by comparing H-maser vs Hg II microwave atomic clocks over 140 days [2]. The Fermi-Segre formula for the hyperfine splitting and the Casimir relativistic correction factor were used to translate frequency drift into variation of α . This yielded an upper limit $\dot{\alpha}/\alpha \leq 3.7 \times 10^{-14}/\text{yr}$.

Another possibility is to use optical atomic frequency standards. These standards are based on strongly forbidden $E1$ -transitions or $E2$ -transitions between the ground state of an atom (ion) and its close metastable excited state. In contrast with the microwave frequency standards, there is no simple analytical formula for the dependence of optical atomic frequencies on α . To reveal this dependence we performed relativistic calculations for a number of atoms and ions which are used or proposed to use as optical frequency standards. Calculations are based on relativistic Hartree-Fock method which is complemented by many body perturbation theory and configuration interaction method to include inter-electron correlations. Relativistic energy shifts were found by numerical variation of the value of α in computer codes. We stress that relativistic corrections can not be reduced to spin-orbit interaction. For example, the s -electron level has the largest relativistic correction and no spin-orbit interaction.

The results are presented in the form

$$\omega = \omega_0 + q_1 x + q_2 y, \quad (1)$$

where $x = (\frac{\alpha}{\alpha_i})^2 - 1$, $y = (\frac{\alpha}{\alpha_i})^4 - 1$ and ω_0 is an experimental frequency of a particular transition. Coefficients q_1 and q_2 are found by fitting calculated energy shifts. Results are presented in the Table.

Using similar approach we also calculated relativistic energy shifts in microwave frequency standards (transitions between different hyperfine structure components) of Cs and Hg⁺. The results are in good agreement with Fermi-Segre-Casimir formula.

Table 1: Relativistic energy shifts for some metastable states of atoms and ions (cm^{-1})

Z	Ion	Ground state	Upper states	ω_0 [3]	q_1	q_2	
20	Ca I	$4s^2$	1S_0 $4s4p$	3P_1	15210	230	0
38	Sr II	$5s$	$^2S_{1/2}$ $4d$	$^2D_{3/2}$	14556	2636	96
			$4d$	$^2D_{5/2}$	14836	2852	160
49	In II	$5s^2$	1S_0 $5s5p$	3P_0	42275	2502	956
			$5s5p$	3P_1	43349	3741	791
			$5s5p$	3P_2	45827	6219	791
56	Ba II	$6s$	$^2S_{1/2}$ $5d$	$^2D_{3/2}$	4844	5402	221
			$5d$	$^2D_{5/2}$	5675	6872	-448
70	Yb II	$6s$	$^2S_{1/2}$ $5d$	$^2D_{3/2}$	24333	9898	1342
			$5d$	$^2D_{5/2}$	22961	8298	1570
80	Hg II	$5d^{10}6s$	$^2S_{1/2}$ $5d^96s^2$	$^2D_{5/2}$	35514	-36785	-9943
			$5d^96s^2$	$^2D_{3/2}$	50552	-19377	-12313
81	Tl II	$6s^2$	1S_0 $6s6p$	3P_0	49451	1661	9042
			$6s6p$	3P_1	53393	5877	8668
			$6s6p$	3P_2	61725	14309	8668
88	Ra II	$7s$	$^2S_{1/2}$ $6d$	$^2D_{3/2}$	12084	15507	1639
			$6d$	$^2D_{5/2}$	13743	19669	-864

[1] W. Marciano, *Phys. Rev. Lett.* **52** 489 (1984).

[2] J. D. Prestage, R. L. Tjoeker and L. Maleki, *Phys. Rev. Lett.* **74** 3511 (1995).

[3] C. E. Moore, *Atomic Energy Levels*, Natl. Bur. Stand. Circ. No. 467 (U.S. GPO, Washington, DC, 1958), Vol. III.