Does the fine structure constant vary with time and distance?

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Were the laws of nature the same ten billion light years from us? Theories unifying gravity and other interactions suggest the possibility of spatial and temporal variation of physical "constants" in the Universe. Current interest is high because in superstring theories which have additional dimensions, compactified on tiny scales, any variation of the size of the extra dimensions results in changes of the 3-dimensional observed coupling constants. At present no mechanism for keeping the internal spatial scale static has been found (for example, our three "large" spatial dimensions increase in size). Therefore, unified theories applied to cosmology suffer generically from a problem of predicting time-dependent coupling constants. Moreover, there is a mechanism which makes all coupling constants and masses of elementary particles to be both space and time dependent, and influenced by local circumstances [1].

The strongest terrestial constraint on the time evolution of the fine structure constant, α, comes from a natural uranium nuclear fission reactor in Gabon, West Africa, which was active 1.8 billion years ago. The relative change of α during this time interval does not exceed 1.2×10^{-7} [2]. However, this limit is based on certain assumptions and covers a relatively small fraction of the age of the Universe. Also, it does not exclude oscillatory dependence of α.

Astrophysical measurements enable us to push the epoch probed back to much earlier times. Any change in α could be detected via shifts in the rest wavelengths of resonance transitions in quasar absorption systems. For example, the ratio of fine structure splitting of an alkali-type doublet to the mean transition frequency is proportional to α^2. A comparison of these ratios in cosmic spectra with laboratory values provides powerful constraints on variability. This method was proposed by J. Bachall and M. Schmidt in 1967.

Recently a new approach has been developed which improves the sensitivity to a variation of α by more than an order of magnitude [3, 4]. The relative value of any relativistic corrections to atomic transition frequencies is proportional to α^2. These corrections can exceed the fine structure interval between the excited levels by an order of magnitude (for example, an s-wave electron does not have the spin-orbit splitting but it has the maximal relativistic correction to energy). The relativistic corrections vary very strongly from atom to atom and can have opposite signs in different transitions (for example, in s-p and d-p transitions). Thus, any variation of α could be revealed by comparing different transitions in different atoms in cosmic and laboratory spectra.

This method provides an order of magnitude precision gain compared to measurements of the fine structure interval. Relativistic many-body calculations are used to reveal the dependence of atomic frequencies on the fine structure constant, for a range of atomic species observed in quasar absorption spectra [3]. It is convenient to present results for the transition frequencies as functions of α^2 in the form

$$\omega = \omega_0 + q_1 x + q_2 y, \tag{1}$$

where $x = (\frac{\alpha}{\alpha_l})^2 - 1, y = (\frac{\alpha}{\alpha_l})^4 - 1$ and ω_0 is a laboratory frequency of a particular transition. New and accurate laboratory measurements of ω_0 have been carried out specifically for this work by Ulf Griesmann, Sveneric Johansson, Rainer Kling, David Learner, Ulf Litzén, Juliet Pickering and Anne Thorne. We stress that the second and third terms contribute only if α deviates from the laboratory value α_l. The initial observational results [4] for two Mg II lines and five Fe II lines suggest that α may have been smaller in the past.

This work has been continued in Ref. [5]. A large set of data consists of 49 quasar absorption systems located between 4 and 11 billion light years from us (starting from 10% of the age of the Universe after Big Bang). Many lines of Mg I, Mg II, Fe II, Zn II, Cr II, Ni II, Si II, Al II and Al III have been included and a study of both temporal and spatial dependence of α has been performed. For the whole sample, $\Delta\alpha/\alpha = (-6.2 \pm 1.5) \times 10^{-6}$. We should stress that only statistical error is presented here. This error is now small and the main efforts are directed towards the study of various systematic effects.

This cosmic spectroscopy method has been extended to study variation of other fundamental parameters. The ratio of the hydrogen atom hyperfine transition frequency to a molecular (CO, CN, CS, HCO^+, HCN) rotational frequency is proportional to $y = \alpha^2 g_p$ where g_p is the proton magnetic g-factor. A preliminary result here is $y = (-2.4 \pm 1.8) \times 10^{-6}$ about 4 billion light years from us. The ratio of rotational and optical frequencies is sensitive to the ratio of the electron and proton masses, hyperfine/optical comparison constrains $\alpha^2 g_p m_e/m_p$. Note that the proton g-factor and mass are functions of the strong interaction constant α_s and vacuum condensates of the quark and gluon fields.

Another method to search for the time variation of α is to study variation of the ratio of frequencies in the laboratory. The strongest laboratory limit on the α variation was obtained by comparing H-maser vs Hg II microwave atomic clocks over 140 days [6]. This yielded an upper limit $\dot{\alpha}/\alpha \leq 3.7 \times 10^{-14}$/yr.

Another possibility is to use optical atomic frequency standards. Any evolution of α in time would lead to the frequency shift. To establish the connection between $\dot{\alpha}$ and $\dot{\omega}$ relativistic calculations of the α dependence of the relevant frequencies for Ca I, Sr II, Ba II, Yb II, Hg II, In II, Tl II and Ra II have been performed [3]. The α dependence of the microwave frequency standards (Cs, Hg^+) has also been accurately calculated.

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