Natural Constants and their Time Dependence

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A group from England, the US and Australia have found a small dependence of the finestructure constant α on cosmic time [1]. They find:

$$\frac{\Delta\alpha}{\alpha} = (0.54 \pm 0.12) \cdot 10^{-5} \tag{1}$$

We have studied such a time dependence within Grand Unified Theories [2]. A time dependence of α can arise, if either the unified coupling constant or the unification scale depend on cosmic time.

If we take the idea of a grand unification seriously, it is implied that the variation of α in time should go parallel to a variation in time of the unifying coupling constant g_{un}. Otherwise the grand unification would only work at a particular time, which does not make sense. Consequently we would expect that all three coupling constants g_1, g_2 and g_3 would be time-dependent. Of particular interest is here a time dependence of the QCD-coupling, i.e. of a_s, since this coupling determines the hadronic mass scale and many other parameters in hadronic and nuclear physics. Also the weak interaction coupling constant would change in time, but the effects are hard to measure.

Consider now the behaviour of α_s in lowest order. It is given by the renormalization group equations as follows:

$$\alpha_s(\mu) \cong \frac{4\pi}{\beta_0 ln\left(\frac{\Lambda^2}{\mu^2}\right)}$$

Here μ is a reference scale, $\beta_0 = -11 + \frac{2}{3}n_f, n_f$: number of quark flavours, and Λ_s is the QCD scale parameter.

Experiments, especially the measurements carried out at LEP and the TEVATRON, give $\alpha_s(M_z) = 0.116 + 0.003/-0.005$ (exp.) $+/-0.003$ (theory). A typical value for the scale parameter is $\Lambda = 213 + 38/-35$ MeV. Of course, if α_s is not only a function of the reference scale, but also of time, we find that also the scale parameter Λ is time dependent. We find for the time dependence:

$$\frac{\dot{\alpha}_s}{\alpha_s} = \frac{2}{ln\left(\frac{\mu^2}{\Lambda^2}\right)} \frac{\dot{\Lambda}}{\Lambda}$$

The relative time dependencies are related by: $\delta\Lambda/\Lambda = (\delta\alpha_s/\alpha_s)\ \ln\ (\mu/\Lambda)$. It follows that the relative change of α_s cannot be uniform, i.e. identical for all reference scales, but it changes logarithmically, if the reference scale changes. For example, we could consider a relative change of α_s at very high energies, e. g. close to the energy, where the grand unification sets in. The corresponding change of Λ would then be larger by a factor ln $(\mu/\Lambda) \cong 38$.

In QCD, the proton mass as well as all other hadronic mass scales are proportional to Λ, if the quark masses are neglected. So if the QCD-coupling or the QCD scale parameter changed in time, we would also expect a corresponding change in time of the nucleon mass and of the masses of the atomic nuclei. Such a change could be observed, for example, through a measurement of the mass ratio m_e/m_p. Since a change of the QCD parameters would not influence the electron mass, the result would be a change of the mass ratio.

Independent of the details of the unification one would expect that that a change in time would be in particular a change in time of the unified coupling constant, defined for example at the point of unification. In order to be specific, we consider as an example the SU(5)-theory with supersymmetry, which is broken at about 1 TeV such that one obtains the Standard Model. The unification takes place at $\Lambda_{\mathrm{GUT}} = 1.5 \cdot 10^{16}$ GeV, where the coupling constant is $\alpha_{\mathrm{un}} = 0.03853$.

A variation in time can also occur through a time dependence of the energy, at which the unification takes place. In the case that only the coupling constant is dependent on the time, one finds that the time change of α and of α_s are related to each other. In fact, both time changes are linked to each other by the ratio $\frac{8}{3}\left(\frac{\alpha}{\alpha_s}\right)$, which is about 10, i.e. the time change of the strong coupling constant is roughly an order of magnitude larger than the time change of the electromagnetic coupling constant.

In the case that the coupling constant remains invariant, but the energy, at which the unification takes place, depends on time, one finds that the time change of the scale Λ for the strong interactions is about 31 times larger than the time change of α, but has the opposite sign. This is interesting. While α increases with a rate of about 10^{-15} per year, Λ and also the nucleon mass goes down with a rate of about 2×10^{-14} per year. The magnetic moments of the proton and of the nuclei would slowly increase, with a rate of about 3×10^{-14} per year.

A change in time of the proton mass and of α can be observed through precise measurements in quantum optics. The wavelength of light, which is emitted in hyperfine transitions, for example in the transitions, which are measured in cesium clocks, is proportional to $\alpha^4 m_e/\Lambda$, which would be time dependent via the time dependence of α and of Λ. On the other hand the wavelength of light, which is generated in atomic transitions, depends only on α and would vary in time accordingly.

The second is currently defined as the duration of 6 192 631 770 cycles of microwave light, which is emitted in the hyperfine transitions of cesium–133. If Λ would change in time, it would mean, that the flow of time, which is measured with cesium clocks, does not fully correspond to the flow of time, tested in atomic transitions. Experiments to look for an effect of this kind have been and are carried out at the Max-Planck-Institute for Quantum Optics in Munich under the leadership of Prof. Haensch.

In the experiment done at the MPQ in Munich one has compared the frequency of a precise cesium clock, called PHARAO, brought in from LPTF in Paris, and the frequency measured in the hydrogen spectrometer, using a 486 nm dye laser. The experiment was similar to an experiment done at the MPQ in 1999, but carried out with higher accuracy. The frequency of the 1S–2S–transitions in hydrogen was measured to 2466 061 413 187 127 (18) Hz. A comparison with the previous result, obtained in 1999, gave a drift of only 24 (50) Hz in 43 months. This gives a change of $2.8(5.7) \cdot 10^{-15}$ per year, and this could have to be compared with the expectation from grand unification, which is $17 \cdot 10^{-15}$. Thus the still preliminary result indicates that cesium clocks are more stable than expected, and the QCD scale parameter Λ does not change on the level of 10^{-14}.

How to interpret this result? Of course, it could be that the astrophysical evidence towards a time change of α is not correct. Further experiments will show whether this is the case. But it could also be that both the scale of grand unification and the value of the unified coupling constant at this scale are time–dependent, in which case one can have a situation, in which the net result for a time change of Λ_c is less than 10^{-14} per year. Nevertheless an effect should be seen on the level of 10^{-15} per year. Further experiments will be done in the future to look for such an effect.

References

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