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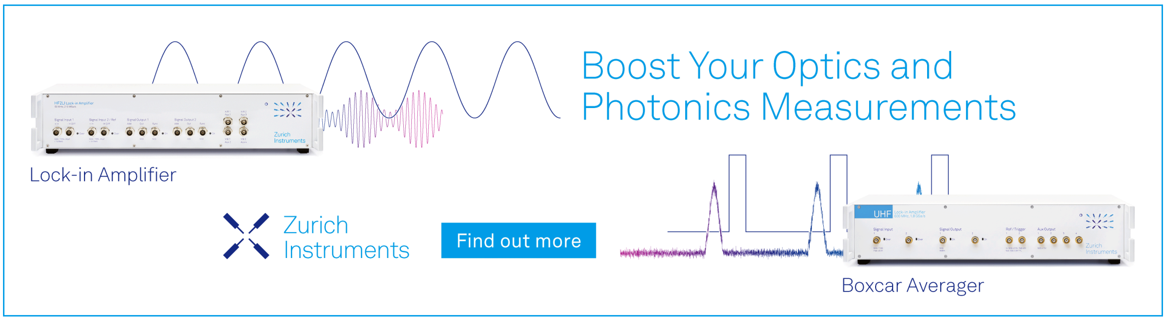

The Oklo Natural Fission Reactors and Improved Limits on the Variation in the Fine Structure Constant

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Abstract. Many dynamical explanations for dark energy imply that the fine structure constant α, which determines the strength of electromagnetic interactions, could vary over cosmological time scales. There are intriguing hints, from absorption spectra of interstellar matter, that α may have been smaller in the distant past than it is today. As first pointed out by Shlyakhter (in the mid-1970s), Oklo data constrains shifts in neutron capture resonance energies over the time since the reactors were last active (about 1.8 billion years ago), and, hence, changes in interaction coupling strengths in the nuclear Hamiltonian like α. Following Shlyakhter's lead, Damour and Dyson concluded (in a study conducted in the mid-1990s) that Oklo data on the absorption of neutrons by ^{149}Sm limit the change in α to less than 0.1 parts per million (ppm) over the last 1.8 billion years. Model dependent considerations indicate that it is difficult to reconcile this upper bound with the behavior of α inferred from interstellar absorption spectra, but there is a tendency in the literature to ignore the Oklo-based limit because of the perception that the nuclear physics invoked in its derivation is fraught with substantial unquantifiable uncertainties. We have addressed these and other uncertainties using a more detailed model of the pertinent state in the compound nucleus ^{150}Sm and an improved choice of nuclear parameters. Central to our calculations are the neutron, proton and charge densities near the surface of the excited ^{150}Sm nucleus. In lieu of experimental data, we argue that the eigenstate thermalization hypothesis allows us to adapt the micro-canonical ensemble treatment of mononuclear configurations formed in heavy ion reactions to the determination of the surface properties of the ^{150}Sm compound nucleus. Key inputs include a study of the energetics of surface diffuseness by Myers and Swiatecki and the leptodermous expansion of the level density parameter, as well as the representation of densities as deformed Fermi functions. In all, four models, tuned to reproduce nuclear data, are used to compute the sensitivity of the relevant ^{150}Sm resonance energy to changes in α. We employ the mean of the four results and their standard deviation as our best estimate for the sensitivity and its uncertainty, respectively. Subject to a weak and testable restriction on the change in light quark masses over the last 1.8 billion years, we deduce that the change in α is less than 0.01 ppm (95% C.L.). This bound reinforces the idea that, of the many dark energy models which predict that fundamental constants do change, only those which suppress the variation of α in the presence of matter are phenomenologically acceptable.

BACKGROUND ON THE COSMOLOGICAL VARIATION OF α AND OKLO

The idea that fundamental coupling constants may vary over cosmological time scales dates back, at least, to the work of Dirac in the 1930s [1]. In the interim, interest in the topic of space-time varying coupling constants has waxed and waned, but it has never been completely abandoned by cosmologists. Prominent among the torch bearers was R. H. Dicke at Princeton. Not only did he, along with C. H. Brans, develop an alternative theory of gravitation in which Newton's constant G is time dependent, but his group also analyzed long-lived β-decays in meteorites for evidence of time dependence in the fine structure constant.

In the last couple of decades, two developments have fueled a growth of activity in studies of the constancy or otherwise of α [2]. One is the emergence of the theoretical paradigm of string theory and inflationary cosmology which has resuscitated the development of extensions to general relativity involving scalar fields. The other is the rigorous analysis of quasar absorption spectra data which suggests that α has a non-trivial history. In the redshift range

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$0.2 < z < 3.7$, α is found to be smaller than today by about 6 parts per million (ppm) [3]. More recent work appears to favor an angular dipole model for variation across the sky, the amplitude of variation being proportional to the look-back time [4].

The Oklo uranium deposits are in 2.1 billion-year old sediment found in the Franceville basin of southeastern Gabon [5,6]. Over a period of 16 years beginning in 1972, fifteen former natural nuclear reaction zones were discovered. The fossilized reactors were in a sufficiently good state of preservation to warrant their detailed geochemical investigation, which has revealed high retention of actinides, rare-earth elements generated in fission, and other decay products of fission fragments. The uranium ore deposits are very heterogeneous in character being primarily present in quartz, clays, and organic material such as solid bitumen, with the percentage uranium by weight ranging from 2% to as much as 15% in uranium rich zones.

Two competing effects imply there is a limited window of operation for natural nuclear fission reactors. The very slow geophysical and geochemical processes responsible for the accumulation of uranium in the Franceville basin are counteracted by the decrease with time of the percentage of uranium-235 in naturally occurring uranium. The Oklo reactors were active about 1.95 billion years ago, when the natural abundance of uranium-235 was about 3.5% (as opposed to its current value of 0.7204%), comparable to the level of uranium-235 in enriched fuel for existing power plants of the nuclear industry. The higher the fraction of uranium-235, the lower the uranium concentration needed for criticality.

TOWARDS EXTRACTION OF THE VARIATION OF α FROM OKLO DATA

It was the late Alexander Shlyakther who recognized how Oklo data could constrain variations in coupling constants of the fundamental interactions over the interval of time since the Oklo reactors ceased to operate [7]. His underlying idea was to focus on thermal neutron capture processes dominated by the properties of a single compound nucleus resonance close to neutron threshold. The reaction n + ^{149}Sm constitutes the prime example, because the neutron capture cross section possesses a resonance less than 0.1 eV above threshold, and even a minute change in the energy E_r of this resonance (in ^{150}Sm) has an enormous effect on the burn up of ^{149}Sm in a thermal neutron ^{235}U reactor.

In principle, a comparison of the distribution of Sm isotopes in spent Oklo fuel with their natural abundances coupled with a trustworthy model for isotope production within the Oklo reactors, would enable one to constrain any change

$$\Delta_r \equiv E_{r,Oklo} - E_{r,now}$$

in the resonance energy E_r. In turn, it can be argued on general grounds that

$$|\Delta_r| \geq |k_\alpha| \frac{|\Delta\alpha|}{\alpha_{now}}$$

subject to a simple testable restriction on the ratio of the relative change in the average m_q of the u and d current quark masses to the relative change in α (in the time since the Oklo reactors were last active). A lower bound on the magnitude of the sensitivity coefficient

$$k_\alpha \equiv \frac{dE_r}{d\ln\alpha}$$

is enough to bound $|\Delta\alpha|$ from above.

Via the Hellmann-Feynman theorem and Green's second identity, one can establish the following inequality relating k_α to the electrostatic potential V_* of the excited compound nucleus ^{150}Sm, its charge density ρ_{150^*} and the charge density ρ_{149} of the ground state of ^{149}Sm [8]:

$$|k_\alpha| \geq L[\rho_{150^*}, \rho_{149}] \equiv \left| \int V_*(\rho_{150^*} - \rho_{149}) d^3r \right|.$$

Knowledge of the charge densities ρ_{150^*} and ρ_{149} would permit the functional $L[\rho_{150^*}, \rho_{149}]$ on the right-hand side of this inequality to be evaluated.

THE DAMOUR-DYSON ESTIMATE

It has been customary to adopt the Damour-Dyson estimate [8] of $L[\rho_{150^*}, \rho_{149}]$ which is based on the simplest model in which the charge distributions are taken to be *spheres of uniform charge density*. The elementary result for the electrostatic potential *inside* such a sphere is used for V_* in $L[\rho_{150^*}, \rho_{149}]$ to relate it to the difference in mean square radial moments $\delta\langle r^2\rangle \equiv \langle r^2\rangle_{150^*} - \langle r^2\rangle_{149}$ of the compound nucleus ^{150}Sm and the ground state of ^{149}Sm, respectively. With a further approximation, namely, the substitution of $\langle r^2\rangle_{150^*}$ by the mean square radial moment $\langle r^2\rangle_{150}$ for the *ground state* of ^{150}Sm, one arrives at the lower bound to L of

$$L_{DD} \equiv \frac{(Ze)^2}{2Q_*^3}\,\delta_{gs}\langle r^2\rangle,$$

where $\delta_{gs}\langle r^2\rangle \equiv \langle r^2\rangle_{150} - \langle r^2\rangle_{149}$ and Q_* is the *equivalent rms radius* of the charge distribution of the compound nucleus ^{150}Sm.

In the evaluation of L_{DD}, the value of Q_* is most critical. Damour and Dyson choose $Q_* = 8.11$ fm, but a more physically reasonable choice would be $Q_* = 6.50 \pm 0.01$ fm, which implies (along with the most recent empirical value of $\delta_{gs}\langle r^2\rangle$),

$$L_{DD} = 2.51 \pm 0.20 \text{ MeV}$$

as opposed to the smaller value of $L_{DD} = 1.1 \pm 0.1$ MeV obtained by Damour and Dyson.

CORRECTIONS TO THE DAMOUR-DYSON ESTIMATE

There are three obvious nuclear physics corrections [9]:

- An ***excitation*** correction which compensates for the replacement of $\langle r^2\rangle_{150^*}$ by $\langle r^2\rangle_{150}$.
- An external ***coulomb*** correction necessitated by the use of the electrostatic potential appropriate to the inside of a uniformly charged sphere (of radius Q_*) to describe the nuclear Coulomb field throughout all space.
- A ***deformation*** correction which accommodates the fact that both the ground state of ^{149}Sm and the state excited in the ^{150}Sm compound nucleus have prolate deformations.

To compute these corrections, more realistic charge densities are required. In the absence of sufficient experimental data on charge densities, deformed Fermi profiles

$$\rho_k = \rho_{0k}\left[1 + \exp\left(\frac{r - C_k[1 + \beta_{2k}Y_{20}(\Omega)]}{z_k}\right)\right]^{-1}$$

fitted to the output of Hartree-Fock + BCS calculations are employed to fix ground state densities ($k =$ n, p, c for neutron, proton and charge densities, respectively) [10]. The scheme devised for estimating the charge density parameters (specifically, the z_k's) of the compound nucleus state in ^{150}Sm requires knowledge of both neutron and proton ground state density parameters.

A variety of self-consistent mean-field studies at non-zero temperature [11-15] suggest that the quadrupole deformation parameters β_{2k} of the excited state in ^{150}Sm should be larger than their values in the ^{150}Sm ground state (because of a decrease in pairing correlations) but cannot exceed these values in the ground state by more than 5%. Fluctuations about the average values of β_{2k}'s are seen to be negligible for excitation energies comparable to that of the near-threshold resonance in ^{150}Sm. For simplicity, the deformations of neutrons and protons are set equal to each other.

Under the assumption that central densities ρ_{0k} are unchanged, it remains to fix the surface diffuseness parameters z_k of this excited state. To this end, the eigenstate thermalization hypothesis is invoked [16], which justifies a microcanonical ensemble analysis. Inputs include a phenomenological description of the energetics of surface diffuseness by Myers and Swiatecki [17] and the ansatz for the level density parameter (inspired by the leptodermous expansion [18]).

$$a = \textstyle\sum_k a_{0k}(1 + \kappa\, z_k/R_k),$$

where R_k is an *equivalent sharp radius* (fixed by the core density ρ_{0k}), and the coefficient κ is chosen so that the dependence of a on mass number agrees approximately with that found for the level density parameter in the back-shifted Fermi gas model. Microcanonical probability distribution functions for the z_ks are generated with the ground state charge density parameters obtained with two different density dependent interactions (SkM* and SLy4) and, independently, two choices of level density formulas (Back-Shifted Fermi Gas and Constant Temperature).

Results for the *sum* of the three corrections (excitation, coulomb and deformation) are given in Fig. 1. This net correction is shown for a reasonable range of the average quadrupole deformation parameter β; for simplicity, the small difference between the average deformations of neutrons and protons is ignored. For each choice of β, the corrections have been averaged over the distributions of the surface diffuseness parameters z_k (taking into account the dependence of the central radii C_k on the z_k's). The band plotted in Fig. 1 delineates the range of values obtained for the net correction when all of the four models for surface diffuseness distributions are used.

The conclusion to be drawn from Fig. 1 is that the net correction to L_{DD} is unlikely to be larger than 25% of L_{DD}.

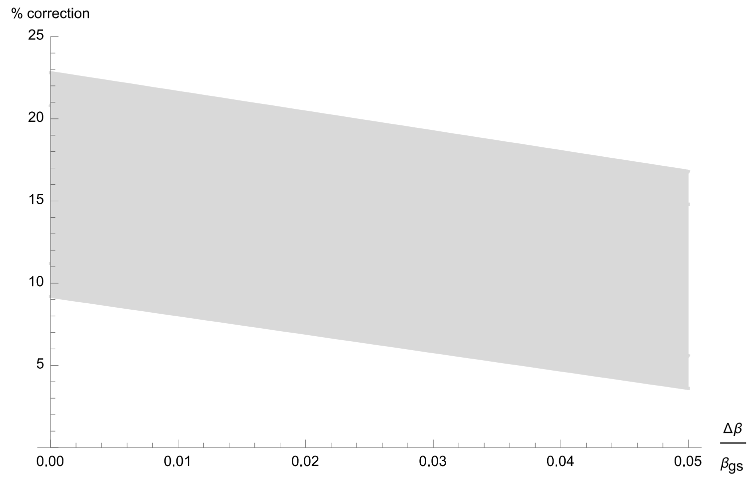

FIGURE 1. The sum of the three corrections to the volume integral of $V_*(\rho_{150^*} - \rho_{149})$. The net correction is plotted as a percentage of L_{DD} for a reasonable range of the fractional difference between the average quadrupole deformation parameter β for the compound nucleus state in ^{150}Sm and its value β_{gs} for the ground state of ^{150}Sm. The band shown demarcates the range of values obtained for the net correction when all four surface diffuseness models are used.

If the scatter in the estimates of corrections is used to infer a mean and a variance for the net correction, then corrected value of L is

$$L_{corr} = 2.18 \pm 0.26 \text{ MeV},$$

where the error in L_{DD} and the error in net correction to L_{DD} have been added in quadrature.

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CONCLUSION

The investigation of corrections to the Damour-Dyson analysis of Oklo data has shown that it should be reliable for order of magnitude purposes. If the above value of L_{corr} is used in conjunction with an improved bound on $|\Delta_r|$ of 0.023 eV (95% confidence level) [19], then the bound implied on the relative change in α since the Oklo reactors were last active is

$$\frac{|\Delta\alpha|}{\alpha_{now}} < 1.1 \times 10^{-8},$$

which is comparable to other estimates of Oklo-based limits (compiled in Table 7 of [6]), but on a more sound footing. This limit, which is an order of magnitude tighter than the Damour-Dyson bound on $|\Delta\alpha|$, puts strong constraints on models which entail a non-trivial cosmological evolution of α [20].

It is encouraging that corrections to the (revised) Damour-Dyson bound for the sensitivity coefficient k_α do not seem likely to give rise to changes of more than 25% or so. It would be of interest to try to employ the recently developed Coulomb energy density functional for atomic nuclei in the evaluation of the sensitivity coefficient k_α [21].

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