Bound on the variation in the fine structure constant α implied by Oklo data

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Undergraduate project (with Dr. E. D. Davis): published as PhysRevC.92.014319 [arXiv: 1503.06011]

Outline

1. What is Oklo? Why is Oklo of interest?
2. How to extract bound on $\Delta\alpha \equiv \alpha_{\text{Oklo}} - \alpha_{\text{now}}$ from Oklo?
   - Damour-Dyson (DD) method
   - Corrections to the DD method
3. What is our bound on $\Delta\alpha$?
4. Implications for dark cosmology?

What?

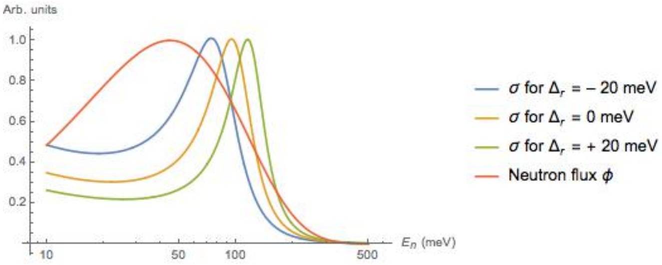
- Natural nuclear fission reactor in Gabon (equatorial West Africa), discovered in 1972 (by CEA, France)

- Operated 1.8 to 2 Gyr ago (redshift $z \simeq 0.14$) like a pulsed light water reactor (Meshik et al., PRL.93.182302)

Why?

- Geochemical data $\longrightarrow$ thermal neutron capture cross-sections σ about 2 Gyr ago
- Any change in σ from present-day values
  $\longrightarrow$ change Δ_r in resonance energy E_r
  $\longrightarrow$ change in α over last $2 * 10^9$ yr (Shlyakhter, Nature.264.340)

$\mathrm{n} + {}^{149}\mathrm{Sm} \rightarrow {}^{150}\mathrm{Sm}^{*}$ (capture of most interest: $E_r = 97.3\,\mathrm{meV}$)



- Small change in $E_r \longrightarrow$ large change in n capture ($\propto \phi \cdot \sigma$)
  $\longrightarrow$ would be seen in Sm Oklo data
- Δ_r from Oklo data consistent with 0 $\longrightarrow$ **very small** bounds on Δ_r

Δ_r(meV)	Reference
4±16	Fujii et al., NPB.573.377
7.2±9.4	Gould et al., PRC.74.024607
1.9±4.5	Onegin et al., ModPhysLettA.27.1250232

$\Delta\alpha$ from Δ_r for ^{150}Sm

Method based on (Damour & Dyson, NuclPhysB.480.37)

- Neglect of dependence on quark parameters (Justify in PhysRevC.92.014319)

$$|\Delta_r| \geq |k| \frac{|\Delta\alpha|}{\alpha_{\text{now}}} \qquad \text{where} \qquad k \equiv \alpha \frac{dE_r}{d\alpha}$$

  Lower bound on $|k|$ enough to set upper bound on $|\Delta\alpha|$

- Exact upper bound on k (negative $\longrightarrow$ lower bound on $|k|$)

$$k \leq \int V_r(\rho_{150^*} - \rho_{149}) d^3 r$$

  Need, in principle, charge densities ρ_{150^*}, ρ_{149} to evaluate
  - V_r = electrostatic potential of excited compound nucleus ^{150}Sm

Uncontrolled approximations in DD bound k^{DD} on k

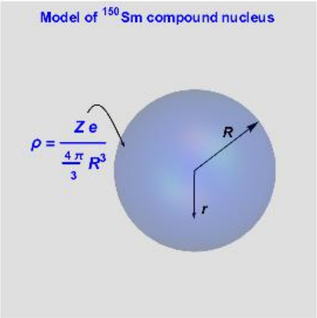
- Estimate V_r assuming charge is sphere of uniform charge density

For all r, use

$$V_r = \frac{Z e}{2 R^3}(3R^2 - r^2)$$

$$\int V_r(\rho_1 - \rho_2) d^3 r \longrightarrow -(\langle r^2 \rangle_1 - \langle r^2 \rangle_2)$$

(any choice of ρ_1, ρ_2)



- Also replace $\langle r^2 \rangle$ for compound nucleus by $\langle r^2 \rangle$ for ground state

$$k \leq k^{DD} \equiv -\frac{(Z e)^2}{2 R^3}(\langle r^2 \rangle_{150} - \langle r^2 \rangle_{149})$$

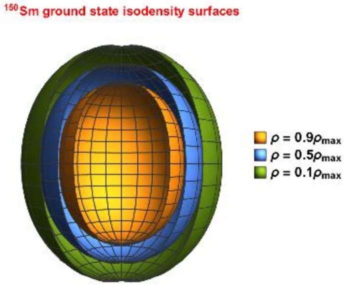
Value of k^{DD} for ^{150}Sm (a numerical correction!)

- R is equivalent rms radius of charge distribution: $R = \sqrt{\frac{5}{3}\langle r^2\rangle_{\text{Expt}}}$
- Damour & Dyson use $R = 8.11$ fm ($\longrightarrow k^{DD} = -1.1 \pm 0.1$ MeV)
  - Much **too big**!
- With *measured* rms radius of ground state ($\longrightarrow R = 6.50 \pm 0.20$ MeV), find for ^{150}Sm

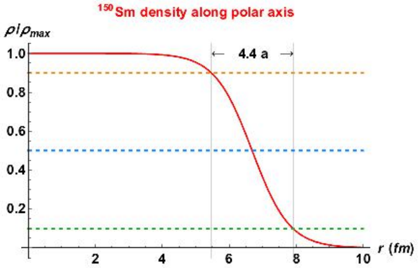
$$k^{DD} \equiv -\frac{(Z\,e)^2}{2R^3}\left(\langle r^2\rangle_{150} - \langle r^2\rangle_{149}\right) = -2.51 \pm 0.20\,\text{MeV}$$

3 physics corrections

- Can identify excitation & external electrostatic potential corrections
- Also use more realistic charge densities $\longrightarrow$ deformation correction



$\propto (1 + \beta\, Y_{20}(\theta))$
Quadrupole deformation $\beta \simeq 0.2$

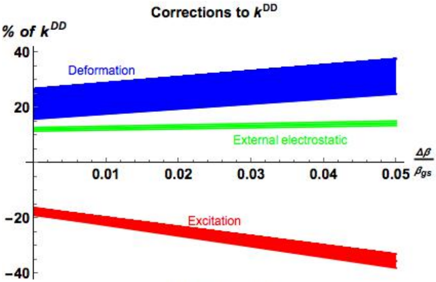


Surface diffuseness $a \simeq 0.50$ fm

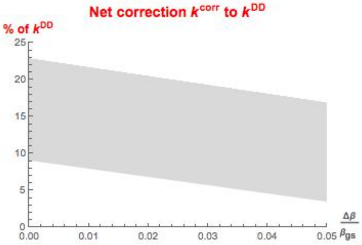
Need to estimate β and a for ^{150}Sm* (increase by a few percent)

Results for our 3 corrections & the net correction

- Use 4 different models of nuclear densities
- Plot results for reasonable range of $\Delta\beta \equiv \beta_* - \beta_{\text{gs}}$ $\quad (0 < \Delta\beta < 0.05\beta_{\text{gs}})$



Big cancellations!



About 15% of k^{DD} on average

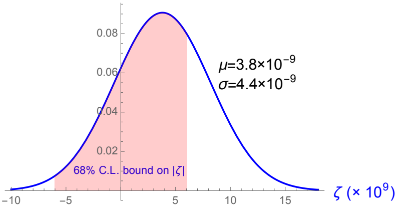
Mean and **scatter** of estimates of net correction $\longrightarrow k^{corr} = 0.33 \pm 0.16$ MeV

- Lower bound on $|k|$

$$k \leq k_B \equiv k^{DD} + k^{corr} < 0 \quad \longrightarrow \quad |k| \geq -k_B = 2.18 \pm 0.26\,\text{MeV}$$

- Upper bound on $|\Delta\alpha|$

$$\text{Use} \quad \frac{|\Delta\alpha|}{\alpha_{\text{now}}} \leq \frac{|\Delta_r|}{|k|} \leq \frac{|\Delta_r|}{-k_B} \quad \& \quad \text{gaussian character of} \quad \zeta \equiv \frac{\Delta_r}{-k_B}$$

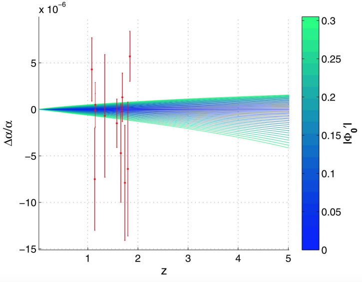


- 95% C.L. bound on $|\Delta\alpha|$

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

Example: runaway dilaton model (of string cosmology)

- Relation between $\Delta\alpha(z)$ & current "speed" Φ'_0 of dilaton



(Martins et al., PhysLettB.743.377)

- Limit on $|\Phi'_0|$ from Oklo 95% C.L. bound on $\Delta\alpha$ at $z \simeq 0.14$

$$\frac{\Delta\alpha}{\alpha} \simeq -\frac{\alpha_{\text{had}}}{40}\Phi'_0 \ln(1+z) \qquad \xrightarrow[z\simeq 0.14]{|\alpha_{\text{had}}|=10^{-4}} \qquad |\Phi'_0| \lesssim 0.03$$

- Undetectable difference in $\Delta\alpha(z)$ for ΛCDM & dilaton models ($z < 5$)

Conclusions

- Revised Damour-Dyson estimate works for orders of magnitude
- New bound on $\Delta\alpha$ at 95% C.L.: $\frac{|\Delta\alpha|}{\alpha_{\text{now}}} < 1.1 \times 10^{-8}$
- For $z < 5$, $\alpha(z)$ does not distinguish dilaton model from ΛCDM

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Thank you for listening!