Reappraisal of the variation in the fine structure constant α implied by Oklo data

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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?

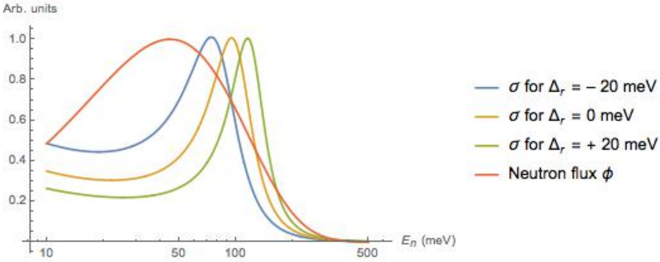
- Natural nuclear fission reactor in Gabon (equatorial West Africa), discovered in 1972 (by CEA, France)

- 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)

$n + {}^{149}\mathrm{Sm} \rightarrow {}^{150}\mathrm{Sm}^*$ (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

More in review IntJModPhysE.23.1430007

Extraction of $\Delta\alpha$ from Δ_r

Standard method based on Damour & Dyson, NuclPhysB.480.37 (1996)

- Wilczek's review of *Birds and Frogs* in Physics Today, August (2015)

  "Dyson's paper, with Thibault Damour, placing empirical limits on the possible time variation of the fine-structure and other fundamental 'constants' is a gem within Birds and Frogs."

- Langacker et al. in PhysLettB.528.121 (2002)

  A re-analysis of the Oklo reactor, aimed at obtaining more accurately the constraints that it imposes on the space of coupling constants, would therefore be welcome. It is possible that this reanalysis would put strong constraints on the variation of Λ_{QCD}/v, as well as on α, and these would be interesting to know.

$\Delta\alpha$ from Δ_r for ^{150}Sm

Two basic ingredients (from 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

More on relation between Δ_r & $\Delta\alpha$

Background in FewBodySyst.56.431

$$|\Delta_r| = \left| k\frac{\Delta\alpha}{\alpha_{\text{now}}} + k_q\frac{\Delta X}{X_{\text{now}}} \right| \geq |\gamma R - | \; |k| \; \frac{|\Delta\alpha|}{\alpha_{\text{now}}}$$

where

$$\gamma = \left| \frac{k_q}{k} \right| \gtrsim 4$$

QCD input

$$R = \left| \frac{\Delta X}{X_{\text{now}}} \Big/ \frac{\Delta\alpha}{\alpha_{\text{now}}} \right|$$

BSM input

First Damour-Dyson inequality holds if $R > 0.5$. (Weak constraint.)

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

- Estimate V_r assuming charge is sphere of uniform charge density

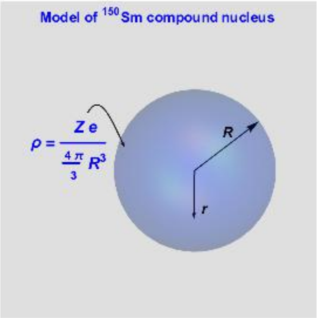
For all r, use

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

$$\int V_r(\rho_1 - \rho_2) d^3 r$$

$$\longrightarrow -(\langle r^2 \rangle_1 - \langle r^2 \rangle_2)$$

(any choice of ρ_1, ρ_2)



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

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

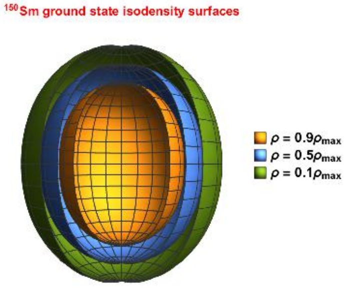
Value of k^{DD} for ^{150}Sm (a numerical correction!)

- 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 $\quad (\longrightarrow k^{DD} = -1.1 \pm 0.1\,\text{MeV})$
  - Much **too big**!
- With *measured* rms radius of ground state $\quad (\longrightarrow R = 6.50 \pm 0.20\,\text{MeV})$, find for ^{150}Sm

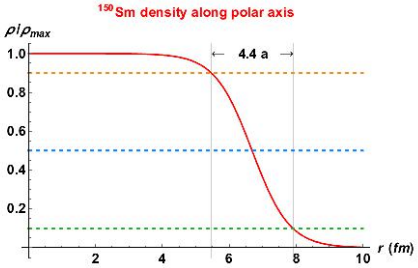
$$k^{DD} \equiv -\frac{(Z\,e)^2}{2R^3}\left(\langle r^2 \rangle_{150} - \langle r^2 \rangle_{149}\right) = -2.51 \pm 0.20\,\text{MeV}$$

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 $\beta \simeq 0.2$

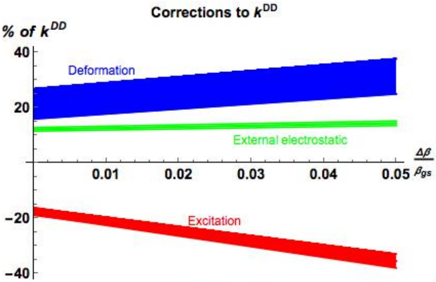


Surface diffuseness $a \simeq 0.50$ fm

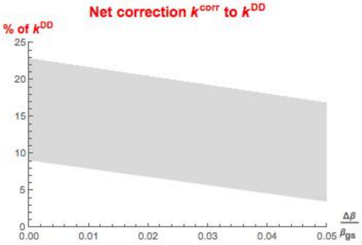
Need to estimate β and *a* for ^{150}Sm* (increase by a few percent)

Results for our 3 corrections & the net correction

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



Big cancellations!



About 15% of k^{DD} on average

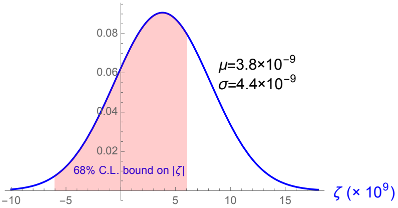
Mean and **scatter** of estimates of net correction $\longrightarrow k^{corr} = 0.33 \pm 0.16$ MeV

- Lower bound on $|k|$

$$k \le k_B \equiv k^{DD} + k^{corr} < 0 \quad \longrightarrow \quad |k| \ge -k_B = 2.18 \pm 0.26\,\mathrm{MeV}$$

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

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



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

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

Comparison with other results for change in α

- Atomic clock bounds on instantaneous rate of change $\dot{\alpha}_{\text{now}}$

$\dot{\alpha}_{\text{now}}/\alpha_{\text{now}}$ (10^{-17}yr^{-1})	Reference
-1.6 ± 2.3	Rosenband et al., Science.319.1808
-0.7 ± 2.1	Godun et al., PRL.113.210801
-2.0 ± 2.0	Huntemann et al., PRL.113.210802

  - Assuming linear variation, our $\Delta\alpha$ bound implies (at 68% C.L.)

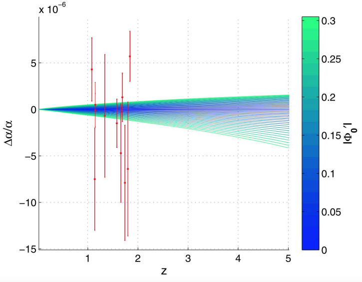
$$\frac{\dot{\alpha}_{\text{now}}}{\alpha_{\text{now}}} < 0.32 \times 10^{-17}\,\text{yr}^{-1}$$

- Bounds on $\Delta\alpha$ over longer time intervals

	Redshift	$\Delta\alpha/\alpha_{\text{now}}$
Meteorites	0.43	$(-0.25 \pm 1.6) \times 10^{-6}$
Quasar absorption spectra	$0.2 - 4.2$	$(-5.7 \pm 1.1) \times 10^{-6}$
Cosmic μwave background	$\sim 10^3$	$-0.013 \mapsto 0.15$
Big-bang nucleosynthesis	$\sim 10^9$	$< 6 \times 10^{-2}$

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.: $\dfrac{|\Delta\alpha|}{\alpha_{\text{now}}} < 1.1 \times 10^{-8}$
- For $z < 5$, $\alpha(z)$ does not distinguish dilaton model from ΛCDM

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Thank you for listening!

Interpretation of Oklo: unified treatment

[IntJModPhysE.23.1430007]

- $$\Delta E_r \equiv E_r(\mathrm{Oklo}) - E_r(\mathrm{now}) = k_q \frac{\Delta X_q}{X_q} + k_\alpha \frac{\Delta\alpha}{\alpha} \qquad \left(X_q = \frac{m_q}{\Lambda_{QCD}} \right)$$

  - k_q independent of mass number A!
    - Conjecture based on study of p-shell nuclei/schematic CN model [PhysRevC.79.034302/PhysRevD.67.063513]
    - k_q susceptible to nuclear matter analysis

  - Order of magnitude estimate for k_q? Model dependent

$\boxed{k_q \simeq +10\,\text{MeV}}$ (Walecka model) $\boxed{k_q \simeq -40\,\text{MeV}}$ (Chiral model)

($k_\alpha \simeq -1\,\mathrm{MeV}$ [NuclPhysB.480.37])

Interpretation of Oklo: Walecka model estimate of k_q

[PhysRevC.79.034302]

- Shift δE_r (due to δX_q) $\xrightarrow[\text{model}]{\text{CN}}$ Depth U_0 of nuclear mean-field

$$\frac{\delta E_r}{U_0} \approx -\underbrace{\left(\frac{\delta m_N}{m_N} + 2\frac{\delta r_0}{r_0} + \frac{\delta U_0}{U_0}\right)}_{\text{Independent of } A} \qquad (R = r_0 A^{\frac{1}{3}})$$

- Walecka model estimate of U_0-term implies (Ignore δr_0)

$$\frac{\delta E_r}{U_0} \approx 7.50\frac{\delta m_S}{m_S} - 5.50\frac{\delta m_V}{m_V} - \frac{\delta m_N}{m_N} \equiv \left(7.50 K_S^q - 5.50 K_V^q - K_N^q\right)\frac{\delta X_q}{X_q}$$

- Uncertain microscopic interpretation of *scalar* S and *vector* V bosons $\longrightarrow$ No first principles calculation of K_S^q, K_V^q

- In PhysRevC.79.34302, K_S^q, K_V^q chosen such that $k_q \sim +10\,\mathrm{MeV}$

Interpretation of Oklo within many-body chiral EFT model

- Plausible paradigm relating U_0 to QCD? "München" model

Ingredients	**Nuclear property**
Large scalar & vector self-energies	Spin-orbit interaction
Chiral $\pi N \Delta$-dynamics + Pauli-blocking	Binding & saturation

NuclPhysA.750.259 NuclPhysA.770.1

Interpretation of Oklo within many-body chiral EFT model

- Plausible paradigm relating U_0 to QCD? "München" model

- Calculation of U for symmetric nuclear matter

Long range interactions

In-medium χPT to 3 loops

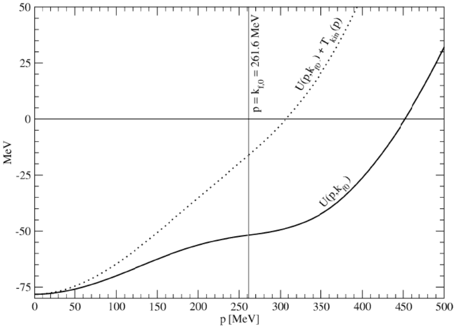
(1 & 2 π exchange, 1 & 2 virtual Δ excitation)

Δ(1232) degree of freedom

Appropriate ($\Delta - N$ mass $\simeq k_{\mathrm{Fermi}}$)
Ensures model phenomenologically satisfactory

Short range interactions

2 contact-terms
Strengths fitted directly to nuclear matter properties



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Sensitivity to quark mass: approximations & results

Long & intermediate range interaction terms $\rightarrow$ $\tilde{U}_0 = \sum_i U_{0i}$

$$\frac{\tilde{U}_0}{m_N} = \underbrace{\frac{\pi}{4}\left(\frac{M_\pi g_A}{2\pi F_\pi}\right)^4 \left[(9+6u^2)\tan^{-1}u - 9u\right]}_{\text{Twice iterated } 1\pi\text{-exchange (2 medium insertions)}} + \dots \qquad \left(u = \frac{k_F}{M_\pi}\right)$$

- In terms of hadronic parameters P (i.e. M_π, F_π, g_A, m_N & Δ)

$$\frac{\delta \tilde{U}_0}{U_0} = \frac{1}{U_0}\frac{\delta \tilde{U}_0}{\delta m_q}\delta m_q = \left[\sum_{P,i} \frac{U_{0i}}{U_0} \underbrace{\left(\frac{P}{U_{0i}}\frac{\delta U_{0i}}{\delta P}\right)}_{=K^P_{U_{0i}}} \underbrace{\left(\frac{m_q}{P}\frac{\delta P}{\delta m_q}\right)}_{=K^q_P}\right]\frac{\delta m_q}{m_q}$$

- Discard all but $P = m_\pi$ term: $\underbrace{K^q_{M_\pi} \approx \frac{1}{2} \gg \text{other } K^q_P\text{'s}}_{\text{Berengut et al. (2013)}}$

- Result: $\frac{\delta \tilde{U}_0}{U_0} = -0.28\frac{\delta m_q}{m_q} \quad \Longrightarrow \quad k_q \sim 10\,\mathrm{MeV}$ (!)

Same as PhysRevC.79.034302 but with *controlled* approximations

Sensitivity to quark mass: approximations & results

2-body contact interaction (of strength B_3)

- Source of largest term in U_0!
- Contributes to part of U_0 linear in density ρ

$$\underbrace{\frac{3\pi}{2m_N}\left[\frac{2\pi}{m_N}B_3 + \tfrac{15}{16}\pi^2\left(\frac{g_A}{2\pi F_\pi}\right)^4 m_N^2 M_\pi\right]}\rho$$

$$\xrightarrow{\rho\to 0} V^{(^1S_0)}_{\mathrm{low}-k}(0,0)+V^{(^3S_1)}_{\mathrm{low}-k}(0,0)$$

[$V_{\mathrm{low}-k}$: Bogner, Kuo, Schwenk (2003)]

- Working assumption: m_q-dependence of $V_{\mathrm{low}-k}$ negligible

$$K^q_{B_3} = 0.52 K^q_{M_\pi} \quad \Longrightarrow \quad \frac{\delta U_{0B_3}}{U_0} = +1.1\frac{\delta m_q}{m_q} \quad \Longrightarrow \quad k_q \simeq -40\,\mathrm{MeV}$$

Less controlled but still plausible? (More details: DOI 10.1007/s00601-014-0909-0)