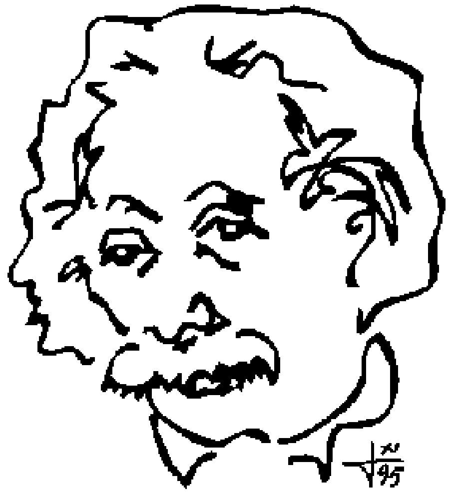
The Fine Structure Variable?

or

“Were the laws of physics any different a long time ago, in a galaxy far far away…?”

Dave Crosby - EBIT Group

Introduction



Equivalence Principle:

In any and every local Lorentz frame, anywhere and anytime in the universe, all the (nongravitational) laws of physics must take on their familiar special-relativistic forms.

Noether's Theorem:

If the potential energy is symmetric with respect to translation along x_i *axis then* p_i *is conserved. If the potential energy is symmetric with respect to rotation about* x_i *axis then* L_i *is conserved.*

A Brief History of a

1856 Weber & Kolrocusch measured ratio of electric and magnetic charges as $3.107*10^{10}$ cm s^{-1}

1857 Kirchoff noticed proximity of this to the speed of light. Maxwell and Riemann subsequently impressed by ‘numerical coincidence’

1905 Planck noticed that $h \sim e^2/c$ *“it seems to me not completely impossible… h has the same order of magnitude as* e^2/c*”*

1909 Einstein remarked *“It seems to me that we can conclude from* $h=e^2/c$ *that the same modification of theory that contains the elementary quantum e as a consequence will also contain as a consequence the quantum structure of radiation.”*

1911 Sommerfeld formally defines α as the ratio of the electrostatic energy of repulsion between two elementary charges, e, separated by one compton wavelength, to the rest energy of a single charge:

$$a = \frac{e^2/(\hbar/mc)}{mc^2} = \frac{e^2}{\hbar c} \sim (137)^{-1}$$

a **grows up**

"Whoah, this is heavy"
"There's that word again, heavy. Why are things so heavy in the future. Is there a problem with the Earth's gravitational pull?" - Doc. Emmett Brown

"e is the representative of the electron theory, h fittingly represents the quantum theory, and c comes from the theory of relativity."

$$E_{n,j} = m_e c^2 f(n, j)$$

$$f(n, j) = 1 - \frac{(Za)^2}{2n^2} - \frac{(Za)^4}{2n^3}\left(\frac{1}{j+\frac{1}{2}} - \frac{3}{4n}\right) - \frac{(Za)^6}{8n^3}\left(\frac{1}{(j+\frac{1}{2})^3} + \frac{3}{n(j+\frac{1}{2})^2} + \frac{5}{2n^3} - \frac{6}{n^2(j+\frac{1}{2})}\right) + \ldots$$

QED - Any electromagnetic phenomena may be described in powers of α

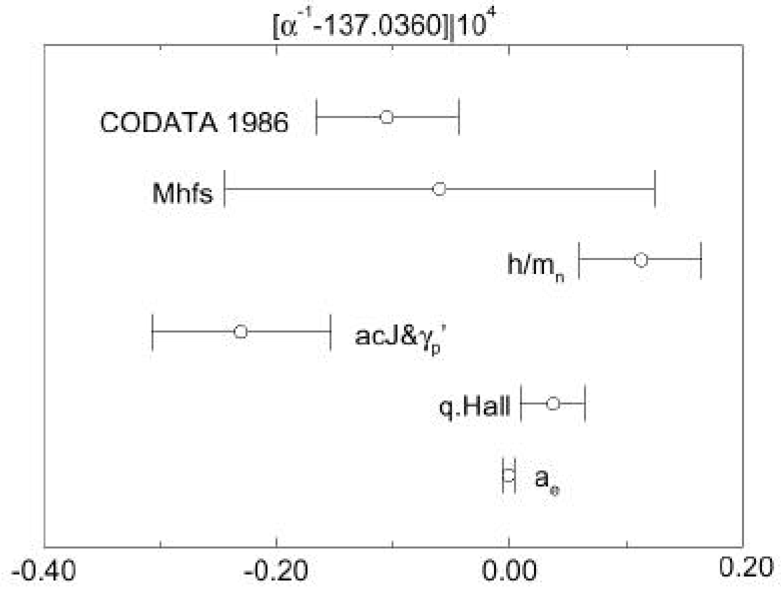
Dimensionless constants are of fundamental importance

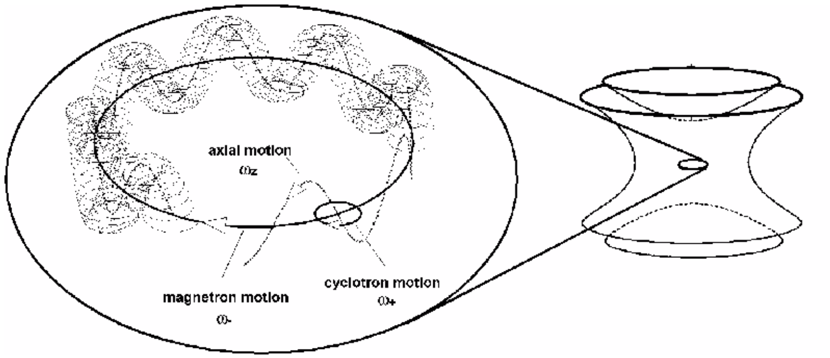
Measurement of a

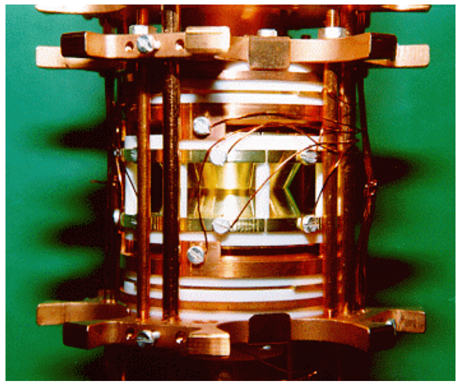
- Neutron de-Broglie wavelength
- Quantum Hall effect
- ac Josephson effect
- simple QED bound systems
- electron anomalous magnetic moment (gold standard)

CODATA[1997]

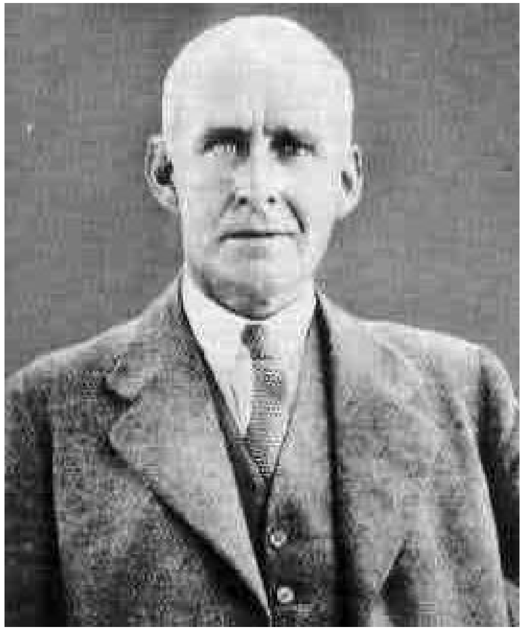
$\alpha(a_e)^{-1}=137.03599993(52)$







Eddington's 'Fundamental Theory'



Eddington Number:

$$N=2*136*2^{256}\sim 10^{79}$$

Other 'Fundamental' Dimensionless Constants:

$$m_N / m_e \sim 1840; \qquad \hbar c / e^2 \sim 137; \qquad e^2 / G m_N m_e \sim 10^{39}$$

$$\frac{c}{H_0}\left(\frac{m_N m_e}{\Lambda}\right)^{1/2} \sim 10^{39}$$

Where H_0 is the Hubble Constant and Λ is Einstein's Cosmological constant - the subject of much current interest

$$\alpha=½(16^2-16)+16=136$$

Beck, Bethe & Riezler in *Naturwissenschaften*, 9 Jan 1931:

Dirac's
'Large Number Hypothesis'

"[large no. coincidences] were not random but conditioned by biological factors" - P.A.M Dirac

In a letter to Nature in 1937 Dirac noted the following coincidence:

$$N_1 = \frac{t_0}{e^2 / m_e c^3} \sim 6*10^{39} = \frac{\text{age of universe}}{\text{atomic light - crossing time}}$$

$$N_2 = \frac{e^2}{G m_N m_e} \sim 2.3*10^{39} = \frac{\text{electric force between proton \& electron}}{\text{gravitational force between proton \& electron}}$$

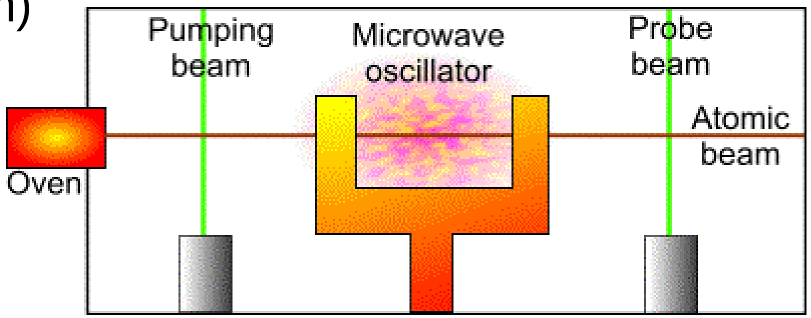
"Any two of the very large dimensionless numbers occurring in Nature are connected by a simple mathematical relation, in which the coefficients are of the order of magnitude unity."

Thus if $N_1 \sim N_2$ and universe not infinitely old then must have varying constants, e.g. $G \sim t^{-1}$

"…the constancy of the fundamental physical constants should be checked in an experiment" - P.A.M Dirac

Variable a:

- Local tests (Atomic Clocks, Oklo Phenomenom)
- Cosmological Tests



Atomic Clocks

Allow limits to be placed on current variation of α.

Compare clocks based on different physical systems - look for change in relative clock rates to each other.

Current best comparison uses H-Maser and Hg^{+} Atomic clock, leading to an upper bound of:

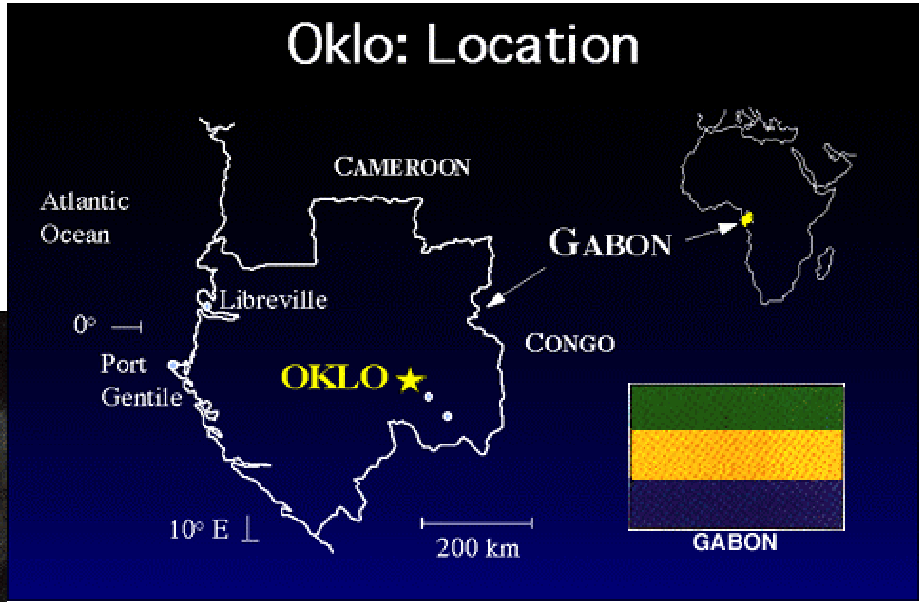
$$\dot{a}/a \leq 3.7 \times 10^{-14}\, yr^{-1}$$

The quickquick Atomic Clock:

1. Atoms out
2. HFS pumped
3. Microwave Oscillator tuned
4. Probe laser checks flip:

The Oklo Phenomenom

Controlled Fission.
Enrico Fermi did it in 1942 in Chicago. Mother Nature did it first, 1.8 bn years ago in West Africa.



15 GigaWatt yr Energy released over ~700 000 years. (Av. Power 20 kw)

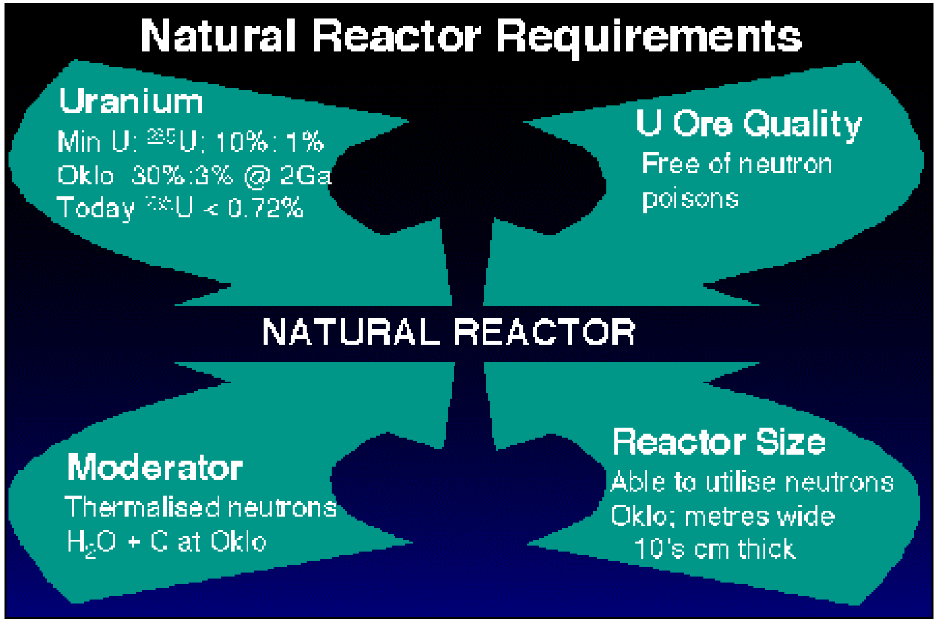
Oklo & the Laws of Physics

Careful analysis of nuclear and geochemical data (up to 2.5cm resolution!) allow reconstruction of operating conditions.

$^{235}U + n \longrightarrow$ fission fragments + 2-3 n

Following neutron capture has strong resonance at thermal neutron energy 98meV, width 63meV.

$^{149}Sm + n \longrightarrow {}^{150}Sm^{*}$



$$\Delta a / a = 0.9\times10^{-7} \text{ to } 1.2\times10^{-7} \text{ in } 1.8\text{bn yr}$$

$$\Rightarrow \dot{a}/a \le 10^{-16}\, yr^{-1}$$

Cosmological Variation of a

Oklo gets us back 1.8 bn yr. To go further away and farther back in time must look to the stars…

- Use Hubble law ($v=H_0 d$) in conjunction with red-shift to approximate age
- Oklo result reassures us that 'tired light' or bulk variations in α are not a problem
- Can extract α from atomic structure

Construction of a Local Standard

Red shift variable prohibits use of single line. Local standard defined by use of a ratio of two or more lines, thus creating a dimensionless parameter:

$$\text{define } (x_*, t_*) \;\&\; (0, t_0)$$

$$(v_a / v_b)_0 = (v_a / v_b)_*$$

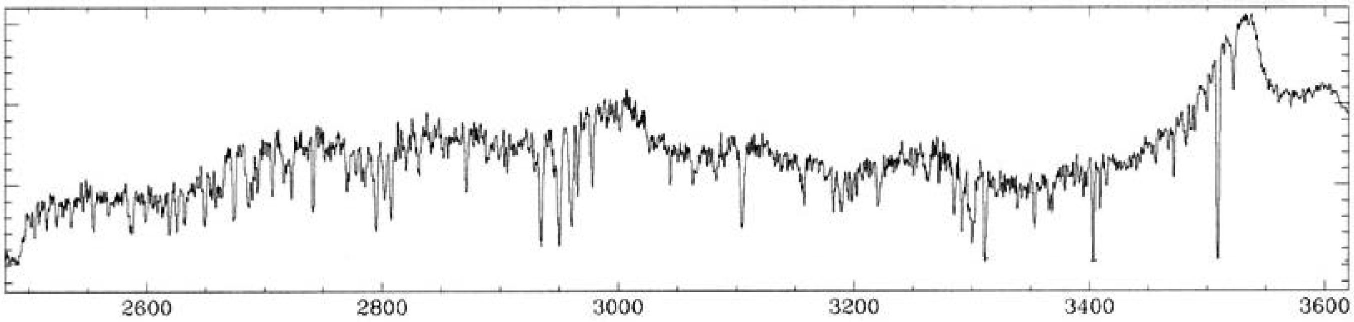
$$\text{Hence, construct } \frac{(v_a / v_b)_0}{(v_a / v_b)_{lab}}$$

e.g. if v_a is a transition between fine structure states and v_b is a resonance transition then:

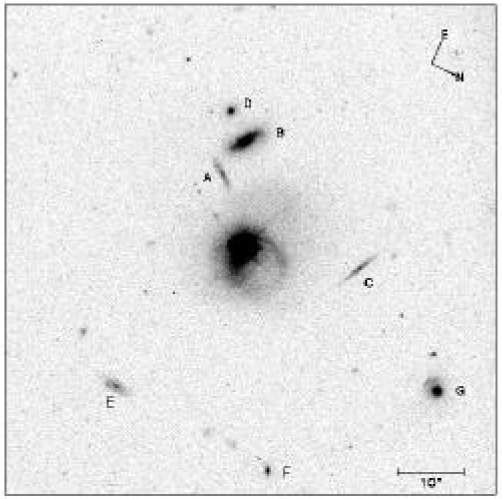
$$\frac{(v_a / v_b)_0}{(v_a / v_b)_{lab}} \approx \frac{\left(a^2\right)_*}{\left(a^2\right)_{lab}}$$

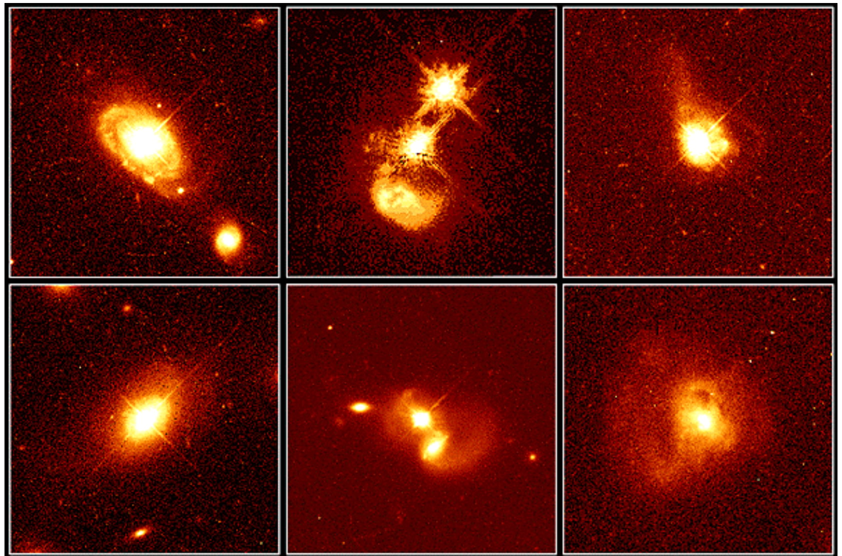
Quasars! Quasars! Quasars!

"Personally I liked the University, they gave us money and facilities. We didn't have to produce anything. You've never been out of college, you don't know what it's like out there… they expect results"
- Dr. Raymond Stantz



Absorption spectra of diffuse clouds illuminated by QSOs





Quasar Host Galaxies HST • WFPC2
PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

Results of QSO observations

"Don't you get technical with me" - C-3PO

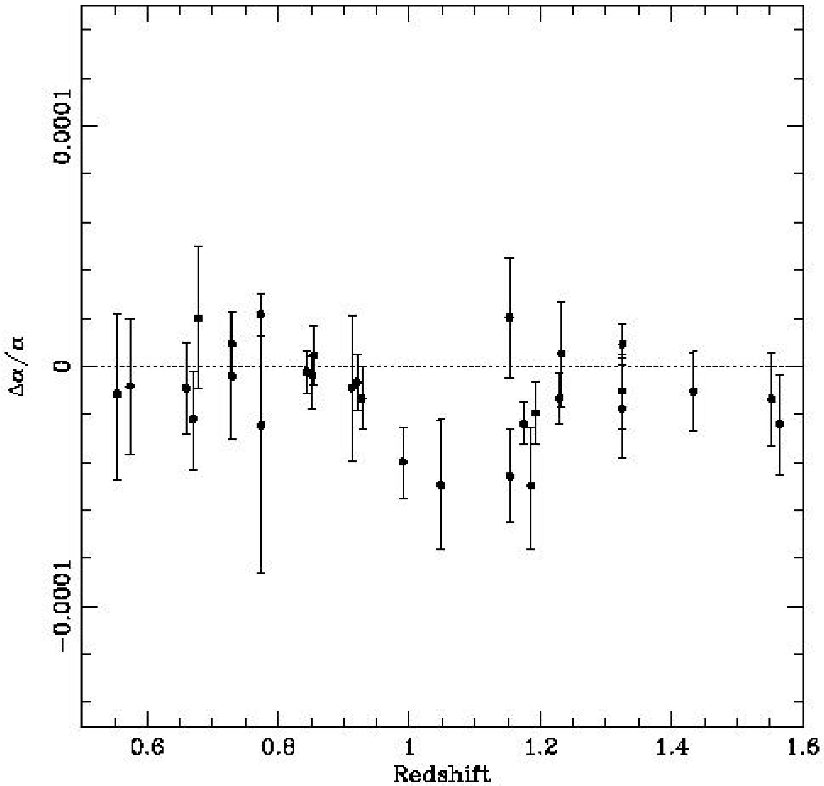
Alkaline Doublet Measure

Sensitive to changes proportional to α
(in first order)
Best observations by Cowie&Songalia(1995)

$$\dot{a} / a \leq 2.1 \times 10^{-15}\, yr^{-1}$$

Mg II & Fe II Combination Measurement

Z of Mg < Z of Fe, thus less higher order α dependence - theoretically achieves order of magnitude better sensitivity.
30 QSOs measured Webb, et al. (1999).



$$\langle \dot{a} \rangle / a = (2.2 \pm 5.1) \times 10^{-16}\, yr^{-1}$$

$$E_z = E_{z=0} + [Q_1 + K_1(\mathbf{LS})] Z^2 [(\tfrac{\alpha_z}{\alpha_0})^2 - 1] + K_2(\mathbf{LS})^2 Z^4 [(\tfrac{\alpha_z}{\alpha_0})^4 - 1].$$

Theoretical Implications*

"We are all interested in the future, for that is where you and I are going to spend the rest of our lives… And remember, future events such as these will affect YOU, in the future" - Criswell, Plan 9 From Outer Space

Superstring Theories.

$$E << E_{Planck} \equiv \sqrt{\hbar c^5 / G} \approx 1.2 \times 10^{19}\, GeV$$

In low energy limit reproduces classical general relativity modified by existence of scalar dilaton. Subsequently, coupling constants and masses of elementary particles depend on dilaton scalar field φ. This leads to space-time dependence

$$\frac{\dot{a}}{a} \sim kH_0(f - f_m)^2$$

Where k is the main parameter determining the efficiency of the cosmological relaxation of the dilaton field φ towards its extreme value φ_m.

Kaluza-Klein Theories.

Treat geometrization in a (4+D) dimension curved space. Truly fundamental constants defined in (4+D) dimensional space, cosmological evolution in extra D dimensions would result in a variation of fundamental constants perceived in 4-dimensional world.

So null results aren't all that disappointing?

(*apparently)