Fundamental Constants

at High Energy

and their time dependence

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Boundary Conditions

Local Laws of Nature

Role of fundamental constants?
What Are Fundamental Constants?

Cosmic Accidents?
Determined by Dynamics?
Changing in Time?
Given by Self-Consistency?
Calculable?
Sommerfeld, 1916........

\[ 1 / \alpha = 137 \]

Pauli (1958): Nr 137, Zürich............

L Lederman, 137 Eola Road

Feynman: 137–how little we know
W. Heisenberg (~30...):

\[ \alpha = 2^{-4} 3^{-3} \pi \]

= 1/137.6...

A. Wyler (1971)

1ppm

\[ \alpha = \frac{9}{8\pi^4} \left( \frac{\pi^5}{2^4 5!} \right)^{1/4} \]

\textit{ratio of two group spaces}
$\alpha^{-1} = 137.035999976$
QED: Most successful theory in science. Merging of electrodynamics, quantum mechanics and special relativity. Renormalizable theory, tested up to 1:10 000 000 (Lamb shift, hyperfine splitting, magnetic moments)

Not expected by those, who created the theory: Dirac, Heisenberg, Pauli, ...
Quantum Field Theory:
Finestructure constant becomes function of energy or scale due to quantum fluctuations of electron-positron pairs

=> partial screening of bare charge of the electron at distances less than the Compton wavelength of the electron
Renormalization Group

Contribution of electron-positron pairs

\[
\frac{d}{d \ln(q/M)} e(q, e_r) = \beta(e)
\]

\text{QED}

\[
\beta(e) = \frac{e^3}{12\pi^2} + ...
\]
Include:
Myons, Tauons, Quarks

$$\beta(e) = \frac{e^3}{12\pi^2} (el. + myons + tauons + u + d + s + c + b)$$
\[ \alpha(200 \text{GeV}) \]

LEP: \[ \sim \frac{1}{127} \]

\[ \alpha(M_Z) = \frac{1}{127.8} \]
About 1.8 billion years ago, in Gabon, Westafrika.

Natural Reactor, which operated about 100 million years.

High concentration of uranium 3% U 235 at that time (today 0.7 %)

Moderator: water from river Oklo

Not commissioned by DOE.
Discovered in the 1970ties by french nuclear physicists
It was found:
Uranium 235 had 0.717 %-
Normally: 0.720 %
=> further investigation
Neutron Capture
\[ \text{Sm}(149) + n \rightarrow \text{Sm}(150) + \gamma \]
Calculation: cross section about 57 ... 93 kb
very large cross section due to
classical resonance just above threshold

\[ E = 0.0973 \text{ eV} \]

Resonance position cannot have changed much
Change less than 0.1 eV

\[ \frac{\alpha(\text{Oklo}) - \alpha(\text{now})}{\alpha} < \frac{1}{10 000 000} \]
Change of alpha per year must be less than \(1/10\ 000\ 000\ 000\ 000\ 000\ 000\ 000\) per year

(if no other parameters change)

=> constraint questionable
Masses:
Where do they come from?
What is mass?

Thus far only one mechanism of mass generation established:

**QCD**

Mass from “no-mass” (dimensional transmutation)

„Anti-screening“ of color – infrared slavery
Mass from no-mass

$1/\lambda$
Experiments:

\[ \Lambda_c \] : about 250 MeV

Mass: confined field energy

Mass in QCD is fully understood
(not, however, the quark masses)
Nucleon Mass in limit of vanishing quark masses:

\[ M = \text{const.} \cdot \Lambda_c \]

const. calculable, but large errors at present.

Exp: 938.272 MeV
\[ M_n = c\Lambda + c_u m_u + c_d m_d + c_s m_s + c_{elm} \Lambda \]

Nucleon Mass in QCD:

Nucleon mass: QCD mass and mass contributions from the quark masses

Example: QCD u d s+c QED

\[ M_p = 938.272\text{MeV} = (861.532 + 20.138 + 19.253 + 35.362 + 1.987)\text{MeV} \]
The Dark Corner of HEP
Fermion Masses: Arbitrary

\[ m_e = 0.511 \text{MeV} = 0.0000021 \times 246 \text{GeV} = 2.000 \times 10^{-30} \text{lb} \]
5 Constants for stable matter

QED

$\alpha$

$m_e$

$m_u$

$m_d$

$\Rightarrow$ Atoms, Nuclei

QCD

$\Lambda$
Constants of Nature
Charged leptons and quarks: (MeV)

\[ m(\text{electron}) / m(\mu) = m(u) / m(c) \ ?! \]

\[ \begin{align*}
\text{electron:} & \quad 0.51 \\
\text{muon:} & \quad 105.7 \\
\text{tau:} & \quad 1777 \\
\text{u:} & \quad 5.3 \\
\text{c:} & \quad 1100 \\
\text{t:} & \quad 174000 \\
\text{d:} & \quad 7.8 \\
\text{s:} & \quad 170 \\
\text{b:} & \quad 4500 \\
\end{align*} \]

(quark masses at 1 GeV)
Quark Masses:

- **Observed:**

\[
m(c) : m(t) = m(u) : m(c) \quad \frac{1}{185} : \frac{1}{190}
\]

\[
m(s) : m(b) = m(d) : m(s) \quad \frac{1}{24} : \frac{1}{23}
\]
predicting t mass
Relations among constants?
e.g. flavor mixing
(slight reduction of nr. of parameters)

\[ \theta_u = \sqrt{m_u} / \sqrt{m_c} \]

\[ \theta_d = \sqrt{m_d} / \sqrt{m_s} \]

similar relations for neutrino masses and mixing angles
Higgs' v.e.v.

\[ v = 246 \text{ GeV} \]

(Fermi constant)

\[ \frac{v}{\sqrt{2}} \approx 174 = m_t ? \]

accident or due to a symmetry?
Time Variation of fundamental constants:
Dirac (~1930)

Time Variation of Newton's constant $G$

of order $10^{-10}$ per year

(only recently excluded)
Observation of fine structure of atomic levels

Quasars 5-7 billion years back
Fine structure of Fe, Ni, Mg, Sn, A
Quasars, back to 11 bn years in time
(challenged by Reimers, Chile, investigating only one quasar)

\[ \Delta \alpha / \alpha = (-0.54 \pm 0.12) \times 10^{-5} \]

Linear App.: \( \frac{d\alpha}{dt} : \alpha \approx 1.2 \times 10^{-15} \text{ per year} \)
Problem with Oklo

invalid, since other parameters change too
$SU(3) \times SU(2) \times U(1) < SU(5)$

$(G, G: 1974)$

$SU(3) \times SU(2) \times U(1) < SO(10)$

$(F-M, G: 1975)$
Grand unification

3 coupling constants

elm., weak and strong int.

reduced to two parameters:

unif. scale and unified coupling

(one constant less)
SO(10)

Fermions in 16-plet

(incl. righthanded neutrinos)
Unification of all forces

Neutrinos are massive
Electroweak theory:

\[ \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1) \]

\[ \text{U}(1): (B-L) \]

*New energy scale for righthanded SU(2)*
If the scale of unification does not change, one finds:

\[ \frac{d\alpha}{dt} : \alpha^2 = \frac{8}{3} d\alpha_s : \alpha_s^2 - \frac{1}{2\pi} (\text{const.}) - \frac{d\Lambda_{\text{Gut}}}{dt} : \Lambda_{\text{Gut}} \]
Coupling Constants in SU(5) with Supersymmetry (similar in SO(10) – Theory)
Magnetic moments of atomic nuclei would change accordingly, per year

\[ \frac{d\Lambda}{dt} : \Lambda \approx 38,8 \cdot \frac{d\alpha}{dt} : \alpha \]

\[ 3,9 \cdot 10^{-14} \]
If only the scale of unification changes, the sign changes:

\[ \frac{d\Lambda}{dt} : \Lambda \approx -31 \frac{d\alpha}{dt} : \alpha \]
Hydrogen

Hyperfine Interaction

21 cm line in astrophysics should change in time
NASA exp.
Time: measured by Cesium clocks

Hyperfine transition, involving the magnetic moment of the cesium nucleus.

Would be affected by time change of QCD scale
Comparison

Difference: 3 CS oscillations per day

Experiment at MPQ Munich
MPQ-Experiment

486 nm dye laser in hydrogen spectrometer

Reference: cesium clock Pharao LPTF Paris

Hydrogen: 1s-2s transition
2 466 061 413 187 127 (18) Hz
Measurements on Hg and Yb

\[ \frac{d\mu}{dt} : \mu = (2.4 \pm 6.8) \cdot 10^{-15} \text{ yr}^{-1} \]

Expected in simple model: about 10 times more

\[ \frac{d\mu}{dt} : \mu = 2 \cdot 10^{-14} \]
Simultaneous change of unif. coupling and unif. scale
Partial Cancellation of effect?
(expected in superstring models)

\[ \frac{8}{3} d \alpha_s : \alpha_s^2 = d \alpha / dt : \alpha^2 + \frac{1}{2\pi} (\text{const.}) - d \Lambda_{Gut} / dt : \Lambda_{Gut} \]

Indication for effect in the new exp. at MPQ

\[ d \Lambda / dt : \Lambda \approx 3 \cdot 10^{-15} / \text{year} \]
Very recently:

Reinhold et al. PRL 96 (2006)
2 quasars, 12 bn. years away

Looking for time variation of ratio proton mass / electron mass

One finds:

$$\frac{\Delta \mu}{\mu} \approx (2 \pm 0.6) \cdot 10^{-5}$$
Hänsch finds the same effect!

Proton mass time dependent

(energy not strictly conserved)

General Relativity: no strict energy conservation
Summary

28 constants of nature, 24 of them mass parameters

Grand unification relates elm., strong and weak interactions.

Time variation of alpha leads to time variation of the QCD scale and of the weak interactions

MPQ Experiment rules out simplest model, but effect seems to be there, about a factor 10 less than naively expected, consistent mit observed variation of electron-proton-massratio.