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「高エネルギー物理学と宇宙像」

重力波実験と精密重力実験 その三

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Content

- Introduction
- Oklo phenomena
- Estimation from QSO spectrum
- Laser ranging to planets
- Proposed experiment

Motivation & History

- Coupling constant

  $\alpha = e^2/(hc) \sim 1/137$ (fine structure C) $(4\pi\varepsilon_0)^{-1}$ for SI unit

  $\alpha_G = Gm_N^2/(hc) \sim 5.9 \times 10^{-39}$ m_N: neucleon mass

- Dirac's Large-Number Hypothesis

  The great numerical value of some pure numbers occurring in physics is due to a variation of some physical constants with time.

- Gamow

  After Teller's publication, an amendment was proposed.

- Dyson

  From the terrestrial occurrence of ^{187}Re and ^{187}Os, e^2 didn't change.

- QSO spectrum

  Light emitted at Remote galaxy reflects early age of universe.

- Requirement of recent unified theories

  an observable coupling constant consists of a scalar field and a fundamental coupling constant, the measurement of which constrains the theory itself

Large-numbers hypothesis

- Ratio of electrostatic and gravitational forces between two protons:

  $e^2/Gm_p^2 = 1.24 \times 10^{36}$

- This is equal to the present age of the universe in terms of the elementary units of time:

  \`les tempons\` $\rightarrow G \propto t^{-1}$

  time necessary to cover a distance equal to the classical radius of an electron = $(e^2/mc^2)(1/c) \sim 10^{-23}$

- The age of the universe is about 10 eons (1 eon=10^9yr) $\sim 3 \times 10^{37}$

- The difference is very small within a factor of $2\pi^2$

Proc. Roy. Soc. A 165, 199, 1938

Phys. Rev. 73, 801, 1948

Teller's objection

- LNH conflicts geological evidence.

- If G decreases in inverse proportion to the age t of the universe, the luminosity of the sun must have decreasing as t^7 and should have been considerably higher in the past geological eras.
- Also, if G used to be larger, the orbital radius of the Earth must have been smaller in the past.

Phys. Rev. Lett. 19, 759, 1967

Gamow's conjecture

- It would be too bad to abandon an idea so elegant and so attractive as Dirac's proposal.
- Is it not possible that, while G remains constant, e^2 increases in direct proportion to the age of the universe?
- Opacity (which determines the nuclear energy production rate) coefficient κ_0 changes in proportion to $e^6 \propto t^3$.
- Sun luminosity increases as $\kappa_0^{-(2n+6)/(2n+5)} \sim t^{-3}$

$L \sim t^{-3}$ as compared with $L \sim t^{-7}$ in case of changing G

Dyson's Objection to Gamow/Teller

- $e^2 \sim t$, $hc/e^2 \sim \ln(tmc^2/h)$ are all excluded when nuclear force unchanged.

- β active isotope ^{187}Re decays to a stable isotope ^{187}Os with a decay energy Δ=2.6keV and a half-life time 4×10^{10}yr.
- Empirical mass formula (Coulomb term) $E_c=0.6\, Z^2 A^{(-1/3)}$ MeV depends on e^2 in proportion.
- The variation of Δ with e^2 comes from the variation of E_c
- $e^2 d\Delta/de^2=(E_c)_{Re}-(E_c)_{Os}=-15.8$MeV.
- If $\tau_{1/2}$ is smaller than 2×10^8yr, Re does not exist on the Earth.
- $\tau_{1/2} \sim \Delta$^{-{2+[1-(Z/137)^2]$^{1/2}$}}=Δ^{-2.835}.
  (Konopinski, Rev. Mod. Phys. 15, 209, 1943)
- Δ at 3×10^9yr ago doesn't exceed the present value $\times 200^{0.353}$.
- → $d\Delta/dt > -4.75\times 10^{-9}$ keV/yr.
- $d\Delta/dt = (e^2 d\Delta/de^2)(e^2 de^2/dt)$
  → $e^{-2}de^2/dt<3\times 10^{-13}$/yr which is smaller by 300 of Gamow

Phys. Rev. Lett. 19, 1291, 1967

Accepted values

- {¥dot G}/G < 10^{-12} /yr
- {¥dot α}/α ∼ {¥dot α_S}/α_S < 10^{-17}/yr

Oklo phenomena

- Natural reactor at Oklo in Gabon, 2 billion years ago
- A. Shlyakhter (Nature 264, 340, 1976)
- T. Damour and F. Dyson (Nucl. Phys. B480, 37, 1996)
- Y. Fujii et al. (Nucl. Phys. B573, 377, 2000)

Oklo Phenomenon

- Uranium mine in Gabon, West Africa
- Evidence of natural reactor discovered (1974)
- Self-sustained fission reactions occurred naturally two billion years ago, lasting millions of years
- Abundance of ^{235}U was much higher (∼3%) in 2 billion years ago than it is (0.7207%)
- Abundance of ^{149}Sm was much smaller than the natural abundance of ^{149}Sm today (13.8%)

Resonant capture decay

- Neutrons absorbed by a process:

$$n + {}^{149}Sm \rightarrow {}^{150}Sm + \gamma$$

- Reaction is dominated by a resonance of E_r=97.3meV which is 7 orders less than typical mass scale of 1MeV
- This is resulted from the cancellation of two effects: repulsive Coulomb force and the attractive nuclear force

Enhancement Mechanism

- Coulomb force is proportional to α
- Nuclear force depends on α_s in more complicated manner
- Suppose α might be different from the present value by $\Delta\alpha$ which causes an appreciable amount of change ΔE_r
- The same should be true for the cross section σ_{149} of the reaction

Example of the enhancement

- ΔE_r=-10meV and T=20℃ gives about 10% increase of the cross section (in thermal equilibrium)

Samples extraction

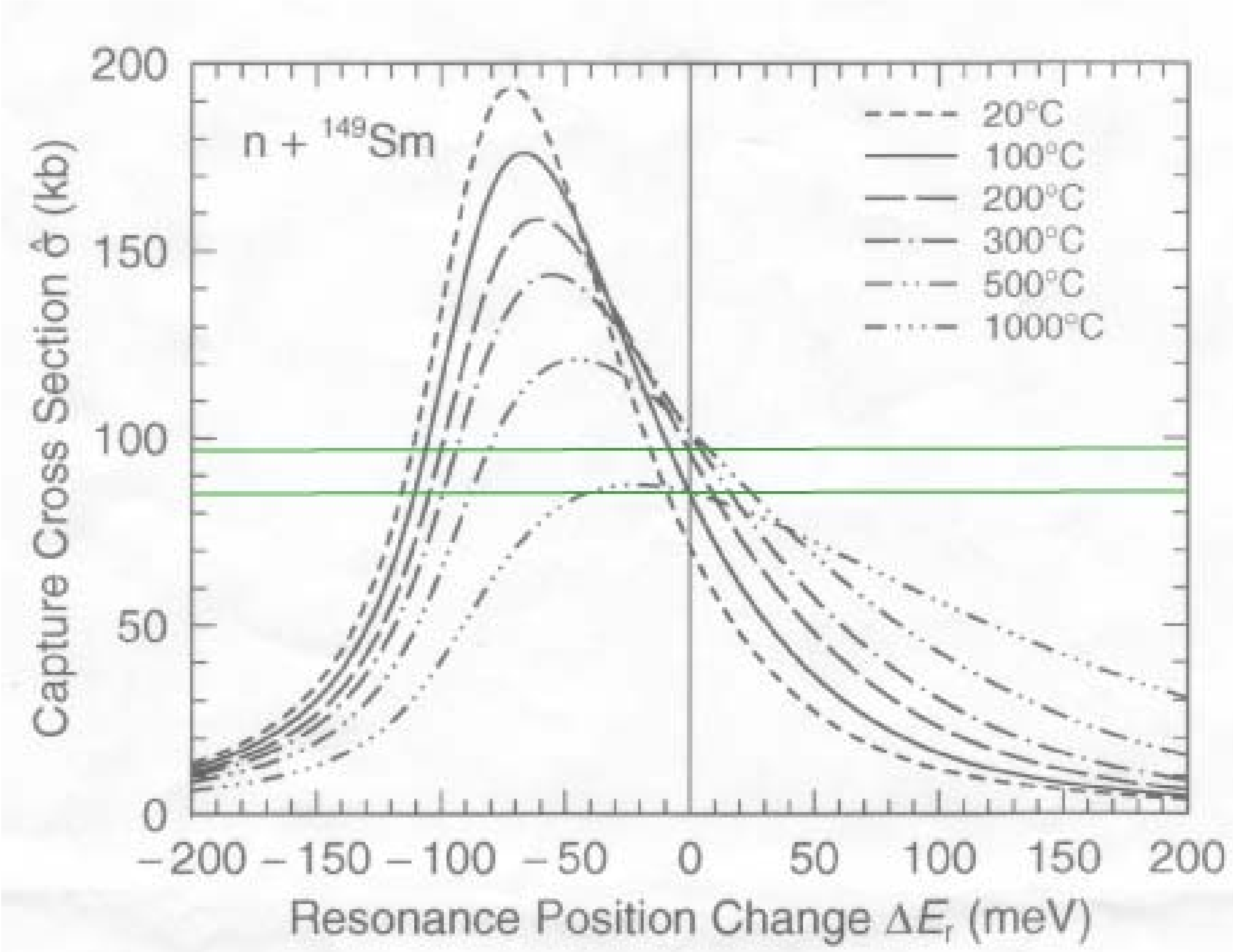
- Fujii et al. re-examined the Shlyakhter' method.
- In the re-examination by Damour and Dyson, certain amount of isotopes might have migrated from outside into the core due to the effect of weathering and other related phenomena.
- Fujii et al. took samples deep underground.

Analysis

- Differential equations for the evolution of the system of ^{235}U, ^{147}Sm, ^{148}Sm, ^{149}Sm
- Solution to σ_{149} = (91$\pm$6) kb for the reaction
- This effective cross section is defined

σ =Sqrt{(4/π)(T/T_0)}σ T_0=20.4°C

Thermally averaged effective cross section for n+^{149}Sm → ^{150}Sm+ γ
Green lines ranges the allowed region by the solution.



Result

- T= 200-400 ℃

- ΔEr = 9±11 meV for right-branch range
  -97±8meV for left-branch range

The right-branch covers the zero, whereas the left-branch is away from zero.

Interpretation to $\Delta \alpha$

- By the analysis of Damour & Dyson,

  $\Delta E_r = (\Delta \alpha / \alpha) M_c$ $M_c \sim -1.1\text{MeV}$
- Fractional change of α:

  $\Delta \alpha / \alpha = -0.8 \pm 1.0 \times 10^{-8}$

  $= 0.88 \pm 0.07 \times 10^{-7}$
- Fractional rate of change:

  {¥dot α}/α $= 0.4 \pm 0.5 \times 10^{-17}$/yr

  $= -0.44 \pm 0.04 \times 10^{-16}$/yr

Oklo's result --Discussion

- The right-branch gives a null result, which agrees well with Shlyakhter's previous conclusion ----rather accidental
- The left-branch indicates that the value of α was indeed different from today's value.

  →less conclusive: ^{155}Gd, ^{157}Gd

  →^{113}Cd will be examined
- Contamination effect for ^{149}Sm: 4% gives $\Delta E_r = 2 \pm 12$meV bringing $\Delta \alpha = 0$.

QSO observation

- Bachall&Schmidt(1967)

  OIII emission lines (5 radio galaxies)

- Wolfe et al (1976)

  MgII fine structure and hydrogen hyperfine absorption lines toward radio source AO 0235+164

- Webb et al (2001)

  3 large optical data sets and 21cm&mm absorption systems

- Srianand et al (2004)

  MgII line, MM analysis, $0.4<z<2.3$, null result

OIII fine-structure lines, 5007 Å and 4959 Å in the emission spectra of five radio galaxies were examined

Ratio $\alpha(z) / \alpha(lab)$ can be computed from the relation

$$[\alpha(z)/\alpha(lab)]^2 = (\delta\lambda/\lambda)_{ob} \times (\delta\lambda/\lambda)_{lab}^{-1}$$

O III emission multiplet lines

Object	z	λ ob	λ ob	$\alpha(z)/\ \alpha(\text{lab})$
Laboratory	0.0	4958.9	5006.8	…..
3C219	0.17	5823.1	5880.4	1.009
3C234	0.18	5875.2	5932.3	1.003
3C26	0.21	6003.2	6060.1	0.990
3C171	0.24	6140.6	6200.5	1.005
3C79	0.26	6230.0	6289.7	0.996

Phys. Rev. Lett. 19, 1294, 1967

Result

- $[\alpha(z)/\ \alpha(\text{lab})]^2 = (\delta\lambda/\lambda)_{ob} \times (\delta\lambda/\lambda)_{lab}^{-1}$

  $\delta\lambda$:fine-structure splitting, λ:weighted mean wavelength (weighted to 2J+1)

- $\alpha(z\sim0.2)/\alpha(\text{lab}) = 1.001 \pm 0.002$ probable error

  Gamow suggestion: $\alpha(z\sim0.2)/\alpha(\text{lab}) \sim 0.8$

A.M.Wolfe et al.

Radio source AO 0235+164

- Hydrogen 1420MHz & optical fine-structure lines $z \sim 0.5$
- $\nu(H) = (16\alpha^2 R)/3(g_p m/2M)[1-3m/M+O(m^2/M^2)+\ldots][1+\alpha/\pi+O(\alpha^2)+\ldots]$ cm^{-1} (hyper fine splitting of H ground state : g_p nuclear g-factor of proton)
- $\nu(Mg^+) = (RZ^2/n^2)[1+O(\alpha^2)+\ldots]$ (Mg doublet)
- $\nu(H)/\nu(Mg^+) = \mathrm{const}\ \alpha^2 (g_p m/2M)(1-3m/M+\ldots)$

Result

- $\nu(H)^*/\nu(Mg^+)^*(\nu(H)/\nu(Mg^+))^{-1}$ $=(1+z_{Mg})/(1+z_H)$

  asterisk superscript denotes quantities at the absorption epoch, z_{Mg} and z_H are the red shift determined from the MgII and H 21cm lines, respectively.

$[\alpha^2(g_p m/2M)]^* = \alpha^2(g_p m/2M)[1.00005 \pm 0.0001]$

$z=0.524$ →look-back time $>0.7\times 10^{10}(50/H_0)$

35% of the age of the universe

$d\ln(\alpha^2 g_p m/M)/dt < 2\times 10^{-14}$ /yr

Further limit obtained by this observation

- $\Delta\nu(Mg^+) = \alpha^2 Z^4 R / 2n^3$ cm^{-1}
- Both hyperfine- and fine-structure splittings are proportional to α^2
- $d \ln(g_p m/M)/dt < \{(1+z_{Mg})^2/(1+z_H)[\Delta\lambda(MgII)/\Delta\lambda(MgII)_0] - 1\}(\Delta t)^{-1} < 8 \times 10^{-12}$ /yr
- $d \ln\alpha/dt < 4 \times 10^{-12}$ /yr

which doesn't improve the result of Bachall & Schmidt

Webb et al.

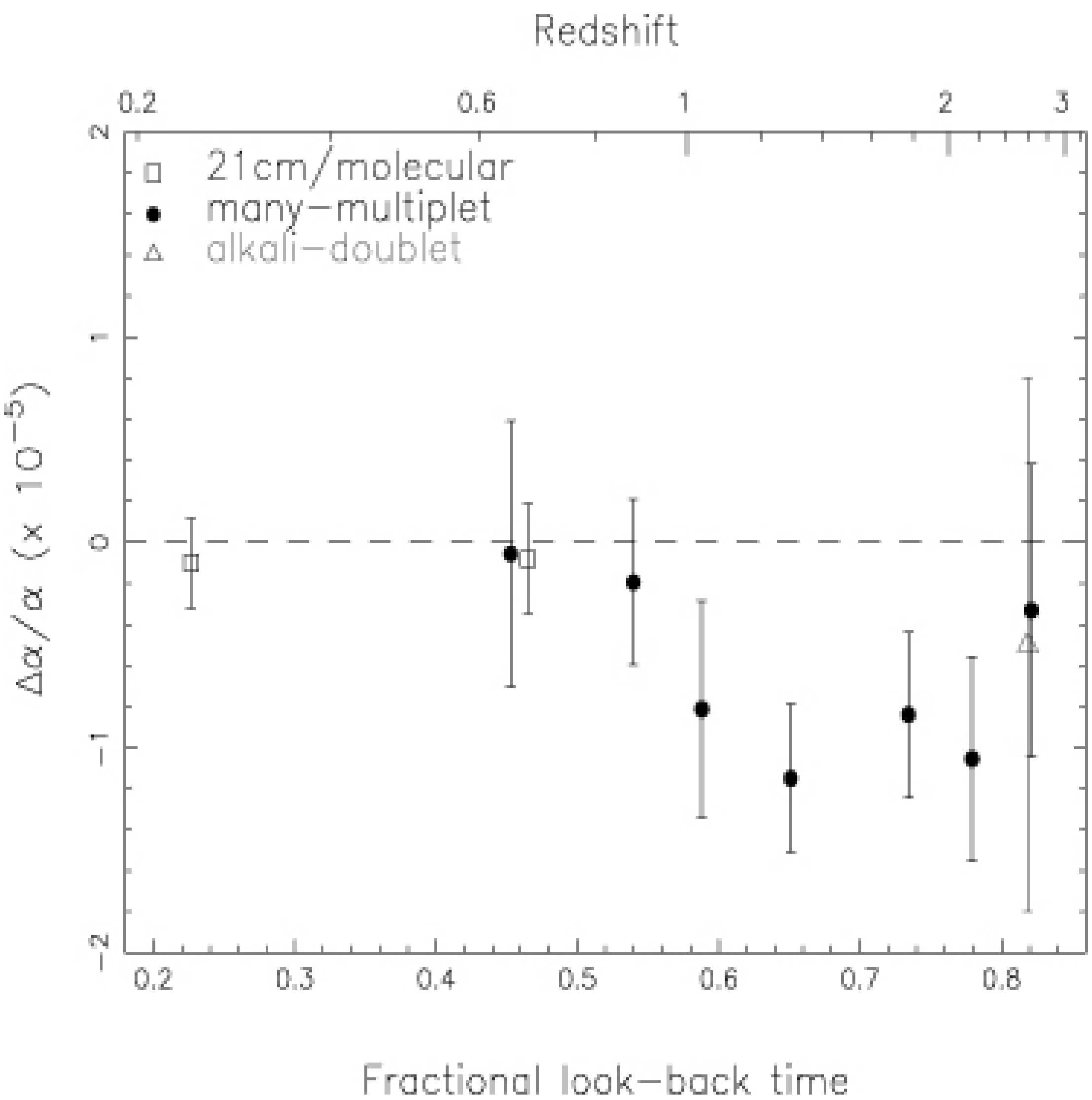
Non-null result by QSO

- Alkari-doublet method & Many Multiplet method
- Observed wave number : $\omega_z = \omega_0 + q_1 x + q_2 y$

  $x=[(\alpha_z/\alpha_0)^2-1]$, $y=[(\alpha_z/\alpha_0)^4-1]$
- First application of MM method:

  FeII, MgI, MgII transitions in 30 absorption systems towards 17 quasars and yielded,

  $\Delta\alpha/\alpha = -1.09 \pm 0.36 \times 10^{-5}$ for $0.5<z<1.6$



$\Delta\alpha/\alpha$=-0.1±0.22×10^{-5} at z=0.25

$\Delta\alpha/\alpha$=-0.08±0.27×10^{-5} at z=0.68

28Mg/FeII systems. New data from HIRES echelle spectrograph

18 Lyman-α absorption systems towards 13 quasars

Two Keck/HIRES absorption system

Transitions of
NiII, AlII, FeII
+ MgI, MgII, AlII, AlIII, FeII

21 SiIV absorption doublets towards 13 quasar spectra

7 solid circles :
49 points, 72 quasars
2 hollow squares:
two HI21cm and molecular absorption systems

H_0=68kms^{-1}Mpc^{-1},
(Ω_M, Ω_Λ)=(0.3,0.7) →13.9Gyr

28/49 were in previous paper

Discussion to QSO non-null result

- The discrepancy is easily removed for a nonlinear time evolution in $\Delta\alpha/\alpha$
- Oklo data constrains $e^2/r_0 \sim \alpha m_\pi c^2$ not clean

  under assumption of constancy of strong interaction and nucleon kinetic energies
- $\Delta X/X = 0.7 \pm 1.1 \times 10^{-5}$ (95% CL) $X = \alpha^2 g_p m_e/m_p$

  (Cowie and Songalia, Ap.J, 453, 596, 1995)
- $\Delta W/W = 2.1 \pm 0.7 \times 10^{-5}$ (68% CL) $W = g_p m_e/m_p$
- In future, CMB probes $z \sim 1000$, $\sim 10^6$ yr of bigbang

  $\rightarrow \Delta\alpha/\alpha \sim 10^{-2} - 10^{-3}$
- Theoretically, Varying speed of light models requires smaller α in the past.

Null result from QSO

- $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$ for $0.4 < z < 2.3$
- Similar analysis like Webb with different line fitting code and independent, uniform, better quality, and well defined data sample.
- Ultra-violet and Visible Echelle Spectrograph (UVES) on ESO Kuyen 8.2m telescope @Paranal observatory

Phys. Rev. Lett. 92, 121302-1, 2004

Selection criteria

- Species with similar ionization potential(Mg II, Fe II, Si II, and Al II)
- Avoid absorption lines that are contaminated by atmospheric lines
- Only systems that have N(Fe II) $>2\times10^{12}$ cm^{-2}
- Non saturated anchor line for redshift measurement
- Avoid subdamped Lyman α systems (N(H I)$>10^{19}cm^{-2}$
- Exclude strongly saturated systems with large velocity spread
- Single component system, Well separated doubles, not complex blend

Result

- Copied figures

Laser ranging to Moon

- Precise scale measurement between Earth and Moon provided more stringent limit on the variation of G
- Also served as the test of the equivalence principle
- Science 265, 482, 1994

Proposed Experiment

- Stability of iodine He-Ne laser
  ^{127}I He-Ne laser 5×10^{-11} (1987) for 14yr
- Reproducibility 5×10^{-12} (1989)
- Energy level $\propto \alpha^2 [1+O(\alpha^2)+\ldots]$ the first term comes from $R(=\mu c \alpha^2/(2h))$ and the second term represents the doublet splitting
- Time standard ^{134}Cs clock
- Result: $d \ln \alpha / dt < 1.8 \times 10^{-12}$/yr

1.5… Bachall

Measurement method of $\Delta\alpha/\alpha$

- Measure transition level $(\propto \alpha^2)$ by Cs clock$(\propto \alpha^4)$
- Splitting of doublet $(\propto \alpha^4)$ by length measurement
- Example of length measurement: Wolfe(1976)

We use two stable laser sources with high finesse optical cavities developed in R&D of gravitational wave detectors

Suppose, two laser sources stably oscillate in different frequencies:

$k_i=k_o(1+\beta_i\alpha^2)$, $k_0=\pi\mu cZ^2\alpha^2/(n^2h)$ and

$\beta_i=Z^2/n^2\{n/K_i-3/4\}$

$K_i=-l-1$ or l according to $j_i=l+1/2$ or $l-1/2$, respectively.

Two beams have different modulation frequencies. We make certain adjustment such that we observe dark fringe simultaneously. Starting from this position of the coincident dark fringe, move the mirror. $N_1(N_2)$ dark fringes have passed in the beam 1(2), we find another coincident dark fringe for $N_1/N_2=k_1/k_2$.

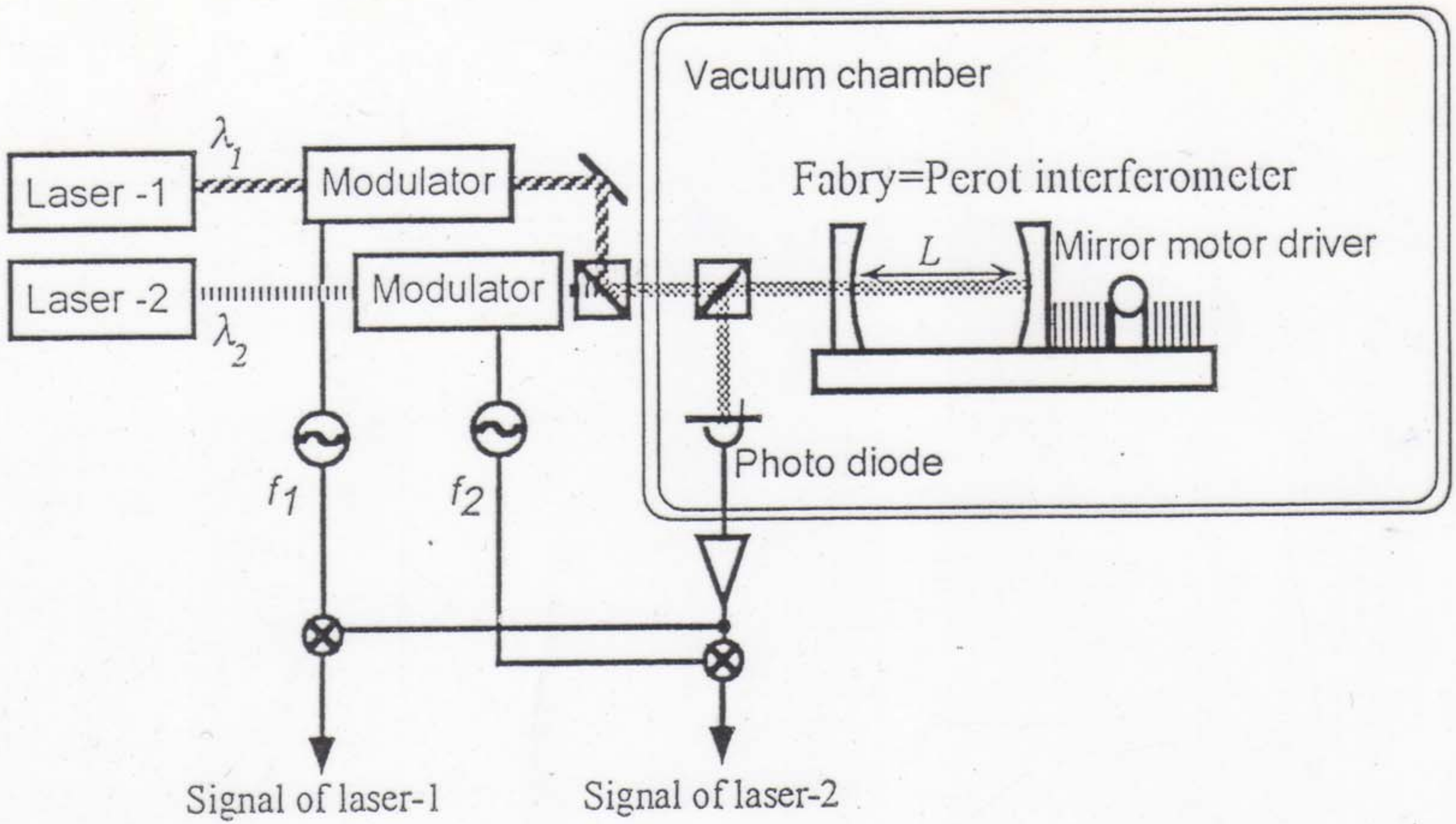


Figure 1: A schematic illustration of the apparatus

Repeated measurement produces a phase shift $\Phi \propto \Delta\beta\ \alpha^2 d(\ln\ \alpha)/dt\ \Delta t\ \Delta L$

If laser wavelength is stable in an accuracy 10^{-13}, the possible limit is $d(\ln\ \alpha)/dt \sim 10^{-17}$/yr

Conclusion

	¥dot G/G	¥dot α / α	¥dot α_s / α_s
Primordial Nucl. Synthesis			1×10^{-13}
Very long-lived nuclei		3×10^{-13}	
Stellar nucl. Synthesis			2×10^{-12}
Oklo phenomenon		1×10^{-17}	5×10^{-19}
Solar-system exp	4×10^{-12}		
Time standards		3×10^{-13}	
Distant QSO		5×10^{-16}	

The observation in future deserves attention