WHAT WE LEARN FROM THE NUCLEAR DATA IN OKLO NATURAL REACTOR

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We reexamined the constraint for the time variation of the coupling constant of the fundamental interaction by studying the isotropic abundance of Sm observed at Oklo natural reactor. Using the most modern and reliable data, together with the study of the isotropic abundance of Gd, we found that the original finding of Shlyakhter is essentially correct, that is, the Oklo data provides us the most stringent limit for the time variation compared with any other methods.

1 Large Number Hypothesis of Paul Dirac

In 1938, Paul Dirac [1] discussed that gravitational and electromagnetic coupling constants G & α might *not* be constants. He suggested that they might evolve as the evolution of our universe. The underlying idea is the followings: The ratio of the gravitational and electromagnetic forces for a pair of protons are written with the electric charge e and the mass of the proton m,

$$Gm^2/e^2/4\pi\epsilon_0 =\sim 10^{-37}. \tag{1}$$

The discussion of Paul Dirac was that the appearance of such large ratio of fundamental interactions is unnatural, at least at the beginning of our universe where everything should be symmetric. If it was the case, the large ratio observed presently is caused by the change of coupling constant according to the time.

The lifetime of our universe t_0 is about $10^{10} years$, whereas the characteristic time of proton is given by $\tau_0 = \hbar/mc^2 \sim 10^{-24}$s. Thus we get a large ratio of two time scale,

$$t_0/\tau_0 \sim 3 \times 10^{41} \tag{2}$$

We can observe the similarity of factors appearing in Eqs.(1) and (2)!! It means that if the gravitational constant G changes inversely proportional to time as

$$G(t) \sim 1/t, \tag{3}$$

at time $t = \tau_0$, the ratio of gravitational and electromagnetic forces is almost unity if all other constants are real constants.

On the other hand, in modern quantum gravitational theories which unify the fundamental interactions at the Planck energy scale 10^{19} GeV, it is expected G, α and m are t-dependent. They are related to the dynamics of scalar field, the features of it is not clarified yet.

Several experimental efforts have been done to check the constancy of G and other constants to check the hypothesis. Among them, the upper limit of the change of G obtained from Viking Project [2] is given as

$$|\dot{G}/G| \lesssim (0.2 \pm 0.4) \times 10^{-11} \mathrm{y}^{-1}. \tag{4}$$

For the time change of α, F. Dyson obtained from the ratio of long-life isotope ^{187}Re and its daughter ^{187}Os [3] as

$$|\dot{\alpha}/\alpha| \lesssim 3 \times 10^{-13} \mathrm{y}^{-1}. \tag{5}$$

From Comparison of Atomic Clocks, A. Godone et al. obtained [4]

$$\dot{\alpha}/\alpha| \lesssim 3 \times 10^{-13} \mathrm{y}^{-1}. \tag{6}$$

From the spectra of quasar (QSO), J.K. Webb et al. obtained the following results [5],

$$|\dot{\alpha}/\alpha| \lesssim 5 \times 10^{-15} \mathrm{y}^{-1}. \tag{7}$$

For strong interaction coupling constant $\alpha_s = g^2/\hbar c$, A.I. Shlyakhter used the nuclear data from Oklo natural reactor to give [6]

$$|\dot{\alpha_s}/\alpha_s| \lesssim 5 \times 10^{-19} \mathrm{y}^{-1}, \tag{8}$$

which gives apparently *far more stringent* upper limit than those obtained by other methods for the time-change of the coupling constant.

As we will see later, the change of α_s and α are interchangeable and if we assume that the strong interaction is constant, we can replace α_s in EQ(8) by α .

2 Oklo Natural Reactor

The reason why the natural reactor was possible 2 billion years ago is given by the following data. The essential fact is that the half life of ^{235}U is smaller than that of ^{238}U.

	^{235}U	^{238}U
Nat. Abund. (Present)	0.720%	99.27%
Half Life	7×10^8years	4.5×10^9years
Nat. Abund. (2×10^9 years ago)	3.7%	96.3%

Based on these facts, K. Kuroda first predicted [7] that with the presence of some amount of water, the vein of uranium could undergo a chin reaction spontaneously. In 1972, the uranium slightly depleted in ^{235}U was detected at French uranium-enrichment plant. It was traced and found out that at Oklo in Gabon Republic, uranium with ^{235}U abundance of 0.4% - 0.5% was mined. It is well proved now that in 2 billion years ago, the reactors were operating in Oklo area (Oklo, Oklobondo, Bagombe). In spite of serious efforts to find the natural reactors in other area, no evidence was found up to now.

3 Isotope Ratio of Sm and Gd in Oklo Area and the Change of Strong Interaction Constant

Four years after the discovery of Oklo, A.I.Shlyakhter published a paper [6] in which he obtained the value given in Eq.(8) from the isotope ratio of Sm isotopes in Oklo. This value is at least 3 orders of magnitude more accurate than any other modern experiments!!!

Now we will trace the method with which A.I. Shlyakhter obtained such precise result from the nuclear data of Oklo. The typical data for Sm isotopes is given by the followings:

	^{147}Sm	^{148}Sm	^{149}Sm	^{150}Sm
1st res.(eV)	3.397	140.4	0.0973	
2nd res.(eV)	18.30	288.8	0.872	
3rd res.(eV)	27.1	422.6	4.95	
half-life(yr)	1.06×10^{11}	7×10^{15}	stable	stable

Another data of our interest are

	$^{147}Sm(\%)$	$^{148}Sm(\%)$	$^{149}Sm(\%)$	$^{150}Sm(\%)$
nat. abund.	15.1	11.3	13.9	7.4
^{235}U ther. FP	1.52×10^{-12}	1.96×10^{-10}	1.11×10^{-8}	-
^{235}U cum. FP	2.25	1.13×10^{-8}	1.07	3.57×10^{-5}

The resonance parameters for the lowest resonance for ^{149}Sm + neutron system are

$$\begin{array}{ll} E_0 & 97.3 \text{ meV} \\ \Gamma_{\rm n} & 0.533 \text{ meV} \\ \Gamma_\gamma & 60.5 \text{ meV} \\ \Gamma_{\rm tot} & 60.8 \text{ meV} \\ s & 1/2\ \hbar \\ I & 7/2\ \hbar \\ J & 4\ \hbar \\ g_0 & 9/16 \end{array} \tag{9}$$

Under the neutron flux of operating Oklo reactor, the ^{149}Sm quickly tuned to ^{150}Sm by capturing neutron, but ^{148}Sm is stable. (^{147}Sm slowly turns to ^{148}Sm.) Isotope ratio of Sm are given by

$$\begin{array}{llll} (^{147}Sm + ^{148}Sm)/^{149}Sm & = (15.1 + 11.3)/13.9 & = 1.889 & : \ natural\ abundance \\ & = (55.34 + 2.79)/0.5546 & = 104.81 & : \ for\ Oklo\ SF84-1469 \\ & = (2.25 + 0.0)/1.07 & = 2.103 & : \ for\ ^{235}U\ cumulative \\ & & & \quad thermal\ \ fission\ products \end{array} \tag{10}$$

A value in Oklo reactor core given in the middle line of above equation differs remarkably from the values of the top and bottom lines. This Oklo value is a typical example of the isotope composition in the reactor core. If we know the value of the neutron fluence and its spectra, we can calculate the theoretical value of the ratio given in the middle line of Eq.(10) by using the neutron capture cross section σ_{149} for ^{149}Sm. The theoretical estimation thus depends on the cross section σ_{149}. Conversely, if we use the experimental value of the middle line of Eq.(10) as a given quantity, we can estimate the cross section σ_{149} at two billion years ago. This estimated cross section is directly related to the position of the neutron capture resonance level. If this position differs from the one observed presently, we can estimate the change of the coupling constant between present one and that of two billion years ago by the consideration given in the following sections.

4 Neutron Capture Cross Section

We assume Bright-Wigner one-level formula for ^{149}Sm,

$$\sigma = \frac{g_0 \pi \hbar^2}{2mE} \frac{\Gamma_{\rm n}\Gamma_\gamma}{(E-E_0)^2 + (\Gamma_{\rm n}+\Gamma_\gamma)^2/4}, \tag{11}$$

where E_0 is the resonance energy. The statistical weight g_0 is written in terms of spin s of neutron, I of target and J of compound nucleus as

$$g_0 = \frac{2J+1}{(2s+1)(2I+1)}. \tag{12}$$

$\Gamma_{\rm n}$ is written as

$$\Gamma_{\rm n} = \frac{2k}{K} v_l \frac{D}{\pi}, \tag{13}$$

where k is the wave number of neutron in the laboratory frame given by

$$k^2 = \frac{2mE}{\hbar^2}, \tag{14}$$

and K is the wave number inside the target nucleus, v_l represents centrifugal and Coulomb effects for emitted particle and D is the level spacing of the compound level. For $l = 0$ neutron, eq.(13) is reduced as,

$$\Gamma_{\rm n} = \frac{2k}{K} \frac{D}{\pi}. \tag{15}$$

On the other hand, the normalized flux Φ_N for Maxwell-Boltzmann distribution is given by

$$\Phi_N = \frac{\exp(-E/T)}{T^2} E dE. \tag{16}$$

where integration with respect to E yields unity.

Thermally averaged neutron capture cross section Σ is written as

$$\Sigma \equiv \int_0^\infty dE \sigma \Phi_N, \tag{17}$$

which is expressed from eqs.(11),(15) and (16)as

$$\Sigma = \int_0^\infty dE \frac{g_0 \pi \hbar^2}{2mE} \frac{2k}{K} \frac{D}{\pi} \frac{\Gamma_\gamma}{(E-E_0)^2 + \Gamma_{\rm tot}^2/4} \frac{\exp(-E/T)}{T^2} E, \tag{18}$$

where

$$\Gamma_{\rm tot} = \Gamma_{\rm n} + \Gamma_\gamma. \tag{19}$$

5 Relation between Isotope Ratio of Oklo and Capture Cross Section

Assuming constant neutron flux ϕ during the operation of Oklo reactor (we can generalize this assumption easily to the time-dependent flux, but for simplicity we use this assumption. The calculated results are independent of this assumption),

$$N_{235} = N_{235}^0 e^{-\sigma_a \phi t}, \tag{20}$$

where N_{235} is the number of Uranium at time t, N^0_{235} is its value at time t=0 (the starting time of the operation of Oklo reactor) and σ_a is the thermally averaged total neutron capture cross section of ^{235}U, somewhat different from the thermally averaged neutron capture fission cross section σ_f. The difference comes from the effect of restitution, that is, some portion of the neutron captured by ^{238}U produces ^{235}U by double beta decay followed by alpha decay. Here we assumed that

$$\sigma_f \phi \gg \lambda_{235}, \tag{21}$$

where λ_{235} is the spontaneous fission decay constant of ^{235}U. We define the number of ^{147}Sm, ^{148}Sm and ^{149}Sm by N_{147}, N_{148} and N_{149}. ^{147}Sm slowly absorbs neutron and turns to ^{148}Sm but ^{148}Sm does not absorb neutron.

The equations for N_{149}, N_{147} and N_{148} are written as

$$\left\{ \begin{array}{rcll} \frac{dN_{149}}{dt} & = & -\sigma_{149}\phi N_{149}+ & N^0_{235}\exp(-\sigma_a\phi t)\sigma_f\phi Y_{149} \\ \frac{dN_{147}}{dt} & = & -\sigma_{147}\phi N_{147}+ & N^0_{235}\exp(-\sigma_a\phi t)\sigma_f\phi Y_{147} \\ \frac{dN_{148}}{dt} & = & +\sigma_{147}\phi N_{147}+ & N^0_{235}\exp(-\sigma_a\phi t)\sigma_f\phi Y_{148} \end{array} \right. \tag{22}$$

where Y_{149}, Y_{147} and Y_{148} are the fission yield of ^{149}Sm, ^{147}Sm and ^{148}Sm. The quantity σ_{149} stands for the thermally averaged neutron capture cross section of ^{149}Sm, which form is given by Eq.(18) and σ_{147} stands for the thermally averagedneutron capture cross section of ^{147}Sm, which form is completely different from Eq.(18) because this nucleus has no low lying resonance level.

To solve Eq.(22) for N_{149}, N_{147} and N_{148}, we need to know the fluence ϕ, the cross section σ_a and temperature of neutron flux. These quantities are obtained from the Oklo data for each reactor core as explained in [8]. Using these quantities, we can calculate the ratio between ^{149}Sm and (^{147}Sm + ^{148}Sm). By comparing this calculated value with the observed value of each Oklo reactor core, we deduce the value of σ_{149} at two billion years ago. What we need finally is to compare this value with the present data. A possible difference of this cross section at two billion years ago and the one at present tells us a possible change of the resonance position which is located at 97.3meV presently as is shown in Eq(9).

6 Change of Fundamental Constant from Oklo Data

We reexamined the Shlyakhter's effort to constrain the time variability of the coupling constants of the fundamental interaction by studying the anomalous isotope ratio in Oklo natural reactor. What's new in our approach are the use of newly obtained data, which are relatively free from contamination, careful treatment of the temperature effect, use of Gd data to confirm the conclusion, and generalized equations which include the effect of flow-in and others. As target reactor cores, we chose 5 samples from two reactor zones [9]. These are newly obtained data taken from deep underground. This new data are thought to be less contaminated than those obtained previously.

According to the method given in the previous sections, we can calculate the possible shift of the neutron capture resonance level. From the detailed analysis [8], we obtained the following value from the analysis of Sm isotopes,

$$\Delta E_0 = 9 \pm 11 meV, \tag{23}$$

where ΔE_0 stands for the shift of the lowest resonance energy of ^{149}Sm. To obtained this value, we took the most reliable estimate of the neutron temperature of T=200-400 C. We performed the same kind of analysis for the Gd isotope data for the same samples. In case of Gd, the results are very sensitive to the small contamination which is caused by the flow-in. Detailed analysis, however, tells us that the resonance sift of Eq.(23) is consistent with the Gd data [8].

Next, we need to relate this resonance shift to the possible change of the fundamental constant. For this, we assumed the relation

$$\Delta E_0/M = \Delta\alpha_s/\alpha_s \tag{24}$$

where M stands for the mass scale corresponding to the resonance level. For the choice of this mass scale, Schlyakhter chose [6] the depth of the nuclear one-body potential of about 50 MeV. Damor and Dyson [10] chose it as about 1MeV from the consideration of the isotope shift data. If we choose it as 50MeV, we obtain

$$|\dot{\alpha_s}/\alpha_s| \lesssim 2 \times 10^{-19}\mathrm{y}^{-1}, \tag{25}$$

and if we choose it as 1MeV, we obtain

$$|\dot{\alpha_s}/\alpha_s| \lesssim 1 \times 10^{-17}\mathrm{y}^{-1}. \tag{26}$$

We see that the original conclusion of Shlyakhter [6] is essentially the same as our result Eq.(25). Such a good coincidence shouldn't be taken so seriously because the original Shlyakhter's analysis is much simpler than ours and the original Oklo data he used is cited nowhere, which is definitely not so good as ours. Nevertheless, the essential finding of Shlyakhter that the Oklo data tells us the most stringent upper limit of the time variation of the fundamental interactions was correct. We like to add finally that the time variation of the electromagnetic coupling constant, if we assume that the strong interaction coupling constant is fixed, has the same values as are given by Eq.(25) and Eq.(26).

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