Temporal variation of coupling constants and nucleosynthesis

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arXiv:astro-ph/0210459 v1 21 Oct 2002

We investigate the triple-alpha process and the Oklo phenomenon to obtain constraints on possible cosmological time variations of fundamental constants. Specifically we study cosmological temporal constraints for the fine structure constant and nucleon and meson masses.

1. Introduction

In previous works, different constraints have been obtained for possible temporal variations of fundamental constants. Recent investigations involved primordial nucleosynthesis [1,2,3,4,5,6,7,8], cosmic microwave background (CMB) [4,9], quasar absorption lines [10,11], stellar nucleosynthesis [12], meteorites [12,13,14], the Oklo phenomenon [8,14,15,16,17] and atomic clocks [8,18,19]. In most of these works temporal variations of the fine structure constant were investigated. Presently the only analysis showing a time variation definitely different from zero stems from the analysis of atomic multiplet spectra in quasar absorption lines through intervening interstellar clouds at $0.5 < z < 3.5$ [10,11].

In this work we investigate the triple-alpha process and the Oklo phenomenon to obtain cosmological constraints on the time variation of the electromagnetic fine structure constant, and the strength of the strong interaction, i.e., the nucleon and meson masses or the QCD scale parameter $\Lambda_{\rm QCD}$.

2. Triple–Alpha process

In stellar nucleosynthesis one of the most sensitive reactions with respect to possible variations of the coupling constants is the triple–alpha process leading to the production of ^{12}C [20,21]. Stellar nucleosynthesis of carbon and oxygen in helium burning of ancient

Table 1
Change of the resonance energy $\Delta E_{\rm R}$ in keV of the 0_2^+–resonance in ^{12}C for variations of the fine structure constant $\alpha_{\rm em}$ in the Coulomb potential, the nucleon mass $m_{\rm N}$ in the kinetic energy term and the meson masses $m_{\rm B}$ in the effective nucleon–nucleon potential with a corresponding enhancement/reduction factor p.

Variation	Energy shift (keV)	
of parameter(s)	$p = 1.001$	$p = 0.999$
$\alpha_{\rm em}$	$+3.88$	-3.89
$m_{\rm N}$	-22.63	$+22.44$
$m_{\rm B}$	$+25.87$	-26.13
$m_{\rm N}$, $m_{\rm B}$[a]	$+3.51$	-3.44
$\alpha_{\rm em}$, $m_{\rm N}$ and $m_{\rm B}$[b]	$+(3.59, 3.64)$	$-(3.51, 3.58)$

[a] We assume that the nucleon mass and the exchanged meson masses scale identically.

[b] We assume that the nucleon mass and the exchanged meson masses scale identically, whereas the fine structure constant scales with a factor 30–60 less [7,23,24].

stars is therefore particularly of interest for two reasons: The process is very sensitive to variations in fundamental parameters and also took place at the same time ($t_{\rm B} \approx 5{-}13\,$Gyr or $z \approx 0.5 - 3$) that absorption lines were being created in the light from quasars due to intervening gas clouds [10,11]. The C/O abundance ratio and the absorption lines in the quasar spectra are therefore both sensitive to variations in coupling constants at the same epoch.

We compare the change of abundance ratios of C/O by variation of fundamental parameters like the fine structure constant $\alpha_{\rm em}$, and/or the nucleon $m_{\rm N}$ and meson masses $m_{\rm B}$. In the first step we investigated the changes of the 0_2^+–resonance in ^{12}C using nuclear microscopic model calculations [20,21] (Table 1).

The observation of the C/O–abundance ratios in ancient stars and their computation in stellar models do not seem to vary by more than a factor 3 (see e.g., [22]). Such a change would be produced in helium burning of Red Giants by a variation of the fine structure constant of not more than $\pm 0.6\,\%$. This leads to the constraint $\Delta\alpha_{\rm em}/\alpha_{\rm em} \approx \pm 6 \times 10^{-3}$ shown in Table 2. The time variation of the fine structure constant through the analysis of atomic multiplet spectra in quasar absorption lines through intervening interstellar clouds of the order of $\Delta\alpha_{\rm em}/\alpha_{\rm em} \approx 10^{-5}$ is still much weaker than the constraint obtained from the triple–alpha process of the order of $10^{-3} - 10^{-2}$ (see Table 2).

Almost the same value for the constraint is obtained when assuming identical linear scaling of the nucleon $m_{\rm N}$ and meson masses $m_{\rm B}$, i.e., $\Delta m_{\rm N}/m_{\rm N} = \Delta m_{\rm B}/m_{\rm B} = \Delta\Lambda_{\rm QCD}/\Lambda_{\rm QCD}$. That the same value is obtained by varying either the fine-structure constant or simultaneously the nucleon and meson masses (the first and fourth line in Table 1) can also be verified in first–order perturbation theory. In this case, the corresponding constraint of the fine structure constant is obtained by assuming that changes in $\alpha_{\rm em}$ are of the order $30 - 60$ larger than for $\Lambda_{\rm QCD}$ [7,23,24]. Therefore, the constraint obtained for $\alpha_{\rm em}$ is one to

Table 2
Approximate constraints upon time variations of the fine structure constant $\Delta\alpha_{\rm em}/\alpha_{\rm em}$ and $\dot{\alpha}_{\rm em}/\alpha_{\rm em}$ $({\rm yr})^{-1}$ for mean look–back times $\bar{t}_{\rm B}$ or corresponding mean red shifts $\bar{z}$, respectively.

$\Delta\alpha_{\rm em}/\alpha_{\rm em}$	$\dot{\alpha}_{\rm em}/\alpha_{\rm em}$ $({\rm yr})^{-1}$
Quasar absorption lines [10,11]: $\bar{t}_{\rm B} \approx 10\,{\rm Gyr}$, $\bar{z} \approx 1.5$	
$(-0.72 \pm 0.18) \times 10^{-5}$	$(-0.72 \pm 0.18) \times 10^{-15}$
Triple–alpha process (this work): $\bar{t}_{\rm B} \approx 10\,{\rm Gyr}$, $\bar{z} \approx 1.5$	
$\pm 6 \times 10^{-3}$	$\pm 6 \times 10^{-13}$
Oklo phenomenon ([16,17] & this work): $\bar{t}_{\rm B} \approx 2\,{\rm Gyr}$, $\bar{z} \approx 0.1$	
$(-3.6 \pm 14.4) \times 10^{-9}$	$(-1.8 \pm 7.7) \times 10^{-18}$

two orders of magnitude more stringent than the one by varying solely the fine structure constant.

3. The Oklo phenomenon

The Oklo phenomenon that occurred about 2 Gyr ago gives the most stringent constraints for variations of fundamental parameters like the fine structure constant as it is seen from Table 2. The Oklo phenomenon refers to a natural fission reactor which was operating at the Oklo uranium mine in Gabon. By examining the isotopic ratios of Sm in the Oklo reactor limits on cosmological time variations of fundamental parameters can be obtained [8,14,15,16,17]. These bounds were derived by calculating the energy shift of a resonant state in ^{150}Sm lying just 0.0937 eV above the threshold of the reaction $^{149}{\rm Sm} + {\rm n} \rightarrow ^{150}{\rm Sm} + \gamma$. The quantity of interest is the energy of that state $E_{\rm R} = Q - E^* = 0.0937\,{\rm eV}$, where Q is the Q–value of the reaction and E^* is the excitation energy of the compound nucleus ^{150}Sm.

We employ the Relativistic Mean–Field theory (RMFT) [25] to calculate the ground–state properties of ^{149}Sm and ^{150}Sm nuclei. We obtain the variation in the Coulomb energy difference between the two nuclei by varying the fine structure constant $\alpha_{\rm em}$ fractionally by 10^{-5}, 10^{-4} and 10^{-3}. The change in the Coulomb energy difference shows a linear relationship with the variation in $\alpha_{\rm em}$. We obtain for the Coulomb energy difference between ^{150}Sm and ^{149}Sm a value of 1.18 MeV, which is only slightly larger than the values obtained from the phenomenological Bethe–Weizsäcker formula. Therefore, the results claimed in recent work [15,16,17] remain unchanged in the light of RMFT–calculations.

We also varied the masses of the nucleon and the σ–, ω– and ρ–mesons. Fractional changes were made of 10^{-5}, 10^{-4} and 10^{-3} in the masses. The total energy difference between the isotopes ^{150}Sm and ^{149}Sm shows again a linear behaviour with the variation in the masses. The change in the total energy difference turns out to be about a factor of 10 larger than the above corresponding change in the Coulomb energy due to the variation in the fine structure constant. This would correspond to a constraint for the fine structure constant that is again as before at least two factors of magnitude more stringent than the

one obtained by solely varying the fine structure constant.

In any case the Oklo phenomenon gives a more stringent constraint than the analysis of atomic multiplet spectra in quasar absorption lines as can be seen from Table 2. A possible explanation could be a non–linear temporal or even a non–monotonic variation of the fine structure constant as has been suggested by some recent papers, since the Oklo phenomenon occurred at a much later time than the absorption lines in the quasar spectra were created.

Acknowledgments

Supported by OTKA-D32513/T037548, FKFP-0242-2000/0147-2001, and by the John Templeton Foundation (983-COS153).

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