A Big-Bang Nucleosynthesis Limit on the Neutral Fermion Decays into Neutrinos

KUSAKABE, Motohiko
(Korea Aerospace University/Soongsil University)
BALANTEKIN, A. B.
(University of Wisconsin, Madison/NAOJ)
KAJINO, Toshitaka
(NAOJ/University of Tokyo)
PEHLIVAN, Y.
(NAOJ/Mimar Sinan Fine Arts University)

The best direct limits on the neutrino magnetic moment come from experiments with reactor antineutrinos [1]. Astrophysical constraints are also derived from studies on the cooling of red giant stars [2], and the helium synthesis in the Big Bang [3]. We consider non-thermal photons produced in the decay of the heavy sterile mass eigenstates in the early universe via the neutrino magnetic moment. We then derive constraints imposed by the observed abundances of all the light elements.

If neutrinos possess magnetic moments, a sterile state would decay into another state by photon emission. The radiative lifetime of such a sterile neutrino is given [4] as

$$\tau_X^{-1} = 5.308 s^{-1} \left(\frac{\mu_{\rm eff}}{\mu_B}\right)^2 \left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3 \left(\frac{m_i}{\rm eV}\right)^3, \quad (1)$$

where, $\mu_{\rm eff}$ is the effective magnetic moment that take us from the heavy mass eigenstate i to the light mass eigenstate j, and $\mu_B = e/2m_e$ is the Bohr magneton. Below, we write the mass of the decaying state as m_X.

If we ignore the mass of final mass eigenstate ($m_j \sim 10^{-2}$ eV), the energy of the produced photon is $E_{\gamma 0} = \sqrt{p^2 + m_i^2}/2$, where p is the initial momentum of the neutrino. Such photons can induce electromagnetic cascade showers, and generate many less energetic nonthermal photons. These nonthermal photons can then disintegrate background light elements [5,6].

We naively assume that the relic abundance of X is the thermal freeze-out abundance for weakly interacting particles [7]. We adopt the method of [6] to calculate the nonthermal nucleosynthesis. We calculate the mass dependent effects of the radiative decay for the first time. In this case, there are three parameters: 1) (n_X^0/n_γ^0), the number ratio of the decaying sterile neutrino state X to the background radiation before the decay of X, 2) τ_X, the lifetime of the decaying eigenstate, or equivalently the neutrino magnetic moment [Eq. (1)], and 3) $E_{\gamma 0}$, the energy of photon emitted at the radiative decay.

Steady state energy spectrum of the nonthermal photons are dependent on m_X. We calculated transfer functions of nonthermal nuclei. A solution to the ^{7}Li abundance problem [8] is found in a parameter region where the photodisintegration of ^{7}Be is induced while those of other light nuclei never occur since the energy of nonthermal photons is below the energy thresholds.

Figure 1 shows the constraints in the (m_X, $|\mu_{\rm eff}|/\mu_{\rm B}$) plane. Higher values of the magnetic moment correspond to shorter lifetimes of X [Eq. (1)]. Below the upper dot-dashed line, the magnetic moment can be constrained from the baryon-to-photon ratio considerations [9]. However, if the magnetic moment is too low, the decay happens after the recombination epoch (lower dot-dashed line). This case is constrained from measurements of γ-ray background and high energy neutrinos [5].

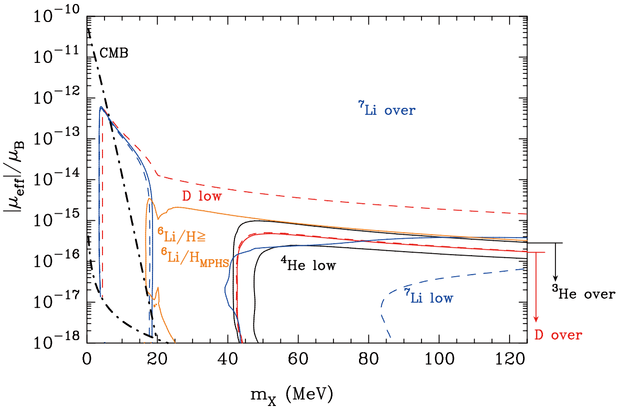

Figure 1: Contours in the (m_X, $|\mu_{\rm eff}|/\mu_{\rm B}$) plane for the adopted constraints of the primordial abundances of D (red), ^{3}He and ^{4}He (black), and ^{7}Li (blue). Regions with the notation, over and low, indicate that they are excluded by overproduction and underproduction, respectively. The regions below solid lines for D, ^{3}He, ^{4}He, and dashed line for ^{7}Li are excluded. The region bounded by two dashed lines for D is also excluded. ^{7}Li is overproduced in the region above solid ^{7}Li lines. The region bounded by two dot-dashed line is excluded by the change of baryon-to-photon [9]. The lower dot-dashed line corresponds to the time of cosmological recombination. This is reprinted from [10].

References

[1] Beda, A. G., et al.: 2012, *Adv. High Energy Phys.*, **2012**, 350150.
[2] Raffelt, G. G., et al.: 1990, *Phys. Rev. Lett.*, **64**, 2856.
[3] Morgan, J. A.: 1981, *Phys. Lett. B*, **102**, 247.
[4] Raffelt, G. G.: 1999, *Phys. Rept.*, **320**, 319.
[5] Ellis, J., et al.: 1992, *Nucl. Phys. B*, **373**, 399.
[6] Kusakabe, M., et al.: 2006, *Phys. Rev. D*, **74**, 023526.
[7] Ressell, M. T., Turner, M. S.: 1990, *Comments Astrophys.*, **14**, 323.
[8] Aoki, W., et al.: 2009, *ApJ*, **698**, 1803.
[9] Feng, J. L., et al.: 2003, *Phys. Rev. D*, **68**, 063504.
[10] Kusakabe, M., et al.: 2013, *Phys. Rev D*, **87**, 085045.