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Sterile Neutrinos in Astrophysical Environments: Big Bang Nucleosynthesis and Supernova Neutrino Process

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In spite of a great success in the discovery of neutrino oscillations, an inconsistency between the three neutrino model and observed neutrino data has left a problem called "neutrino anomalies". The sterile neutrino, as a hypothetical particle, is coined to resolve the anomalies. Although the obscurity of nuclear reactions in reactors should be explained, the sterile neutrino, as a possible solution, has attracted intensive discussions. Especially the role of sterile neutrinos has been importantly discussed in the astrophysics as well as the neutrino physics. In this proceeding, we review how the sterile neutrino affects two astrophysical environments; one is big bang nucleosynthesis (BBN) and the other is supernova (SN) neutrino process.

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1. Introduction

Neutrinos are one of signatures left by the cosmos. We can more deeply investigate the universe by the detection of cosmic neutrinos or understand properties of neutrinos by the astrophysical observations. For example, neutrinos from the supernova (SN) 1987A give important information of supernova explosion mechanism [1] and observations of solar neutrinos give a clue for the discovery of neutrino oscillation [2, 3]. However, in the neutrino physics, experiments of LSND [4], MiniBooNE [5], reactor [6] and gallium experiments [7] reported that neutrino oscillation data are not partly in accord with three neutrino model. This is called ‘neutrino anomalies’, which remains as an unexplained problem. Although understanding of nuclear physics in reactors should be established for this problem [8, 9, 10], the existence of inactive fourth neutrino called "sterile neutrino" can be a possible solution to explain the anomalies.

The existence of sterile neutrinos affects the astrophysical processes as well as analysis of neutrino oscillation experiments. Among various astrophysical processes, in this proceeding, we focus on two astrophysical processes: big bang nucleosynthesis (BBN) [11] and SN neutrino process [12]. In the BBN study, we adopt the sterile-active neutrino model with large extra dimensional universe proposed in Ref. [13]. In the SN neutrino process, we use the 3+1 neutrino model constrained by short base line and IceCube experiments [14]. Based on the two studies [11, 12], we briefly review how the sterile neutrino can affect the astrophysical processes.

2. Sterile neutrinos in BBN

First, in this section, we show the effects of the sterile neutrino in five dimensional universe on BBN. This model suggests that the only sterile neutrino can propagate the five-dimensional universe and the sterile neutrino interacts with active neutrinos via mixing [13]. When we apply this model into BBN, the cosmic expansion rate in the early universe can be changed by the five-dimensional model and energy density of sterile neutrinos. This cosmic expansion rate affects the primordial abundances by changing the freeze-out time of nucleosynthesis.

More specifically, in the five-dimensional universe with a large extra dimension, the cosmic expansion rate H is given as [15],

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 \simeq \frac{8\pi G}{3}\rho + \frac{\mathscr{E}}{a^4}, \tag{2.1}$$

where a is the scale factor of the four-dimensional space, G the Newton’s constant, ρ the energy density and $\mathscr{E}$ the integration constant from the Einstein’s field equation for a five-dimensional model. The energy density ρ is separated to the ordinary (ρ_{ord}) and sterile neutrino energy density (ρ_{ν_s}). To determine ρ_{ν_s}, we exploit the following rate equation

$$\frac{x}{Y_{EQ}}\frac{dY_{\nu_s}}{dx} = -\frac{\Gamma_{\nu_s}}{H}\left[\left(\frac{Y_{\nu_s}}{Y_{EQ}}\right)^2 - 1\right], \tag{2.2}$$

where x is defined as a ratio of sterile neutrino mass (m_{ν_s}) to the temperature T and Y is a ratio of the number density to the entropy density in the co-moving unit volume. Sub-index EQ and ν_s, respectively, stand for the equilibrium state and sterile neutrino. By assuming that the sterile neutrino interacts with other particles via only neutrino mixing, the interaction rate Γ_{ν_s} can be written as [16, 17]

$$\Gamma_{\nu_s} = P_{as} \langle \Gamma_{\rm weak} \rangle \,, \tag{2.3}$$

where P_{as} is the flavor change probability of active-sterile neutrinos and $\langle \Gamma_{\rm weak} \rangle$ is the averaged weak interaction rate. In one-active and one-sterile neutrino mixing model, if we consider the mixing between muon and sterile neutrino, the averaged weak interaction rate becomes $\langle \Gamma_{\rm weak} \rangle \to \Gamma_\tau = 2.9 G_F^2 T^5$ [18], where G_F is the Fermi constant. For the flavor change probability between sterile and active neutrinos, we adopt the wave packet treatment [11]. As a result, the flavor change probability is proportional to the following effective mixing angle

$$\sin^2 2\tilde{\theta} = \frac{\sin^2 2\theta}{Q_\alpha(\theta, \delta m^2, E_{\rm res}; T, E)}, \tag{2.4}$$

where θ is bare mixing angle of active-sterile neutrinos and Q_α is defined as

$$Q_\alpha(\theta, \delta m^2, E_{\rm res}; T, E) = \sqrt{\sin^2 2\theta + \cos^2 2\theta \left[1 + \frac{C_\alpha G_{\rm F}^2 T^4 E^2}{\cos 2\theta \alpha \delta m^2} - \left(\frac{E}{E_{\rm res}} \right)^2 \right]^2 }. \tag{2.5}$$

Here, α is the fine structure constant and flavor dependent constants are $C_e = 1.22$ (for ν_e) and $C_{\mu,\tau} = 0.34$ (for ν_μ and ν_τ). The resonance energy is given as

$$E_{\rm res} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\varepsilon_s}}, \tag{2.6}$$

where the shortcut parameter ε_s is defined as difference between the geodesic in the bulk D_B and the brane D_b, *i.e.*, $\varepsilon_s = (D_b - D_B)/D_b$. The second and third terms in the squared bracket of Eq. 2.5 are related to the matter and extra-dimensional effects, respectively. By these two effects, resonances in neutrino oscillation can occur. When the resonance condition is satisfied before the decoupling of the sterile neutrino, the ρ_{ν_s} is enhanced. This condition depends on parameters of $\theta, E_{\rm res}$ and δm^2. The enhanced ρ_{ν_s} increases the cosmic expansion rate during BBN, which makes an earlier freeze-out time of nucleosynthesis. By the observations of primordial abundances, the enhanced ρ_{ν_s} is constrained. Namely, BBN gives a constraint on mixing parameters of $\theta, E_{\rm res}$ and δm^2. A detail analysis of results is shown in Ref. [11]. For the primordial lithium problem that the predicted ^{7}Li abundance is higher than observations, this model cannot be a solution. As a solution of the primordial lithium problem, the decay of heavy sterile neutrino can be considered [19, 20].

3. Sterile neutrinos in supernova neutrino process

Second, we show effects of sterile neutrino on the SN neutrino process. With the SN1987A model and hydrodynamical model in Ref. [21], we consider the three active neutrinos and one sterile neutrino. The time evolution of 3+1 neutrinos can be described by the following Schrödinger-like equation,

$$i\frac{\rm d}{\rm dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \hat{H} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix}, \tag{3.1}$$

The total Hamiltonian is composed of vacuum ($\hat{H}_{vacuum}$) and matter ($\hat{H}_{matter}$) terms as follows,

$$\hat{H}_{\text{vacuum}} = U\text{diag}(0, \frac{\delta m_{21}^2}{2E_\nu}, \frac{\delta m_{31}^2}{2E_\nu}, \frac{\delta m_{41}^2}{2E_\nu})U^\dagger, \tag{3.2}$$

$$\hat{H}_{\text{matter}} = \text{diag}(V_{CC} + V_{NC}, V_{NC}, V_{NC}, 0), \tag{3.3}$$

where U and E_ν stand for the 4×4 unitary mixing matrix and neutrino energy, respectively. The mass squared difference is $\delta m_{ij}^2 \equiv m_i^2 - m_j^2$. Mixing parameters, *i.e.*, mixing angle and mass squared difference, are taken from Refs. [14, 22].

We find that the 3+1 neutrino model involves multiple resonances by the Mikheyev-Smirnov-Wolfenstein (MSW) effect in SN explosion environments. In the inner region ($M_r \sim 1.6$ solar mass), the first resonance occurs between sterile and electron neutrinos. Since there is not enough source to make sterile neutrinos near by the core, we can assume that the initial luminosity of sterile neutrino is zero. Then, by the first resonance, electron neutrinos are converted to sterile neutrinos in the region, whereas electron neutrinos cannot be created by sterile neutrinos due to the zero initial luminosity of sterile neutrino. Hence, in the inner region where the heavy nuclei such as ^{92}Nb, ^{98}Tc and ^{138}La are produced, neutrino process by electron neutrinos are suppressed. As a result, the abundance of heavy nuclei is decreased compared to the three active neutrino model.

In the outer region where light elements are produced, the electron neutrinos are recovered by the MSW effect. In this process, the recovered quantity of active neutrinos depends on the mass hierarchy. For the normal hierarchy case, electron neutrinos are fully recovered in the outer region, but not in the case of inverted hierarchy. Therefore, the abundance ratio of ^{7}Li and ^{11}B is different between the two kinds of mass hierarchies. By the analysis of SiC X grains, this ratio of ^{7}Li and ^{11}B can be inferred [23]. In other words, the viability of 3+1 neutrino model with the two mass hierarchies can be constrained from investigations on the neutrino process [12].

4. Summary

In this proceeding, we review the effects of the sterile neutrino on BBN and SN neutrino process. First, we assume the sterile neutrinos in five dimensional universe and show how they affects the primordial abundances by changing the cosmic expansion rate. Second, we give an overview of the SN neutrino process in the 3+1 neutrino model by adopting the global fitted mixing parameters. In both cases, the multiple resonances by the sterile neutrino can change the nuclear abundances, which is constrained by the astronomical observations. In the end, this means that the astrophysical processes can be another important tool to verify the sterile neutrino model.

References

[1] K. Hirata *et al.* [Kamiokande-II Collaboration], *Observation of a neutrino burst from the supernova SN1987A*, Phys. Rev. Lett. **58**, 1490.

[2] T. Kajita, *Nobel Lecture: Discovery of atmospheric neutrino oscillations*, Rev. Mod. Phys. **88**, 030501, 2016.

[3] A. B. McDonald, *Nobel Lecture: The Sudbury Neutrino Observatory: Observation of flavor change for solar neutrinos*, Rev. Mod. Phys. **88**, 030502.

[4] A. Aguilar *et al.* [LSND Collaboration], *Evidence for neutrino oscillations from the observation of $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam*, Phys. Rev. D **64**, 112007, [hep-ex/0104049].

[5] A. Aguilar *et al.* [MiniBooNE Collaboration], *Event Excess in the MiniBooNE Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations*, Phys. Rev. Lett. **105**, 181801, [hep-ex/1007.1150].

[6] G. Mention *et al.*, *Reactor antineutrino anomaly*, Phys. Rev. D **83**, 073006, [hep-ex/1101.2755].

[7] C. Giunti and M. Laveder, *Statistical Significance of the Gallium Anomaly*, Phys. Rev. C **83**, 065504, [hep-ph/1006.3244].

[8] D. A. Dwyer and T. J. Langford, *Spectral Structure of Electron Antineutrinos from Nuclear Reactors*, Phys. Rev. Lett. **114**, no. 1, 012502, [nucl-ex/1407.1281].

[9] J. Ashenfelter *et al.* [PROSPECT Collaboration], *First search for short-baseline neutrino oscillations at HFIR with PROSPECT*, Phys. Rev. Lett. **121**, no. 25, 251802, [hep-ex/1806.02784].

[10] J. Petković, T. Marketin, G. Martínez-Pinedo and N. Paar, *Self-consistent calculation of the reactor antineutrino spectra including forbidden transitions*, J. Phys. G **46**, no. 8, 085103, [nucl-th/1903.06192].

[11] D. Jang, M. Kusakabe, and M. K. Cheoun, *Effects of sterile neutrinos and an extra dimension on big bang nucleosynthesis*, Phys. Rev. D **97**, 043005, [nucl-th/1611.04472].

[12] H. Ko, D. Jang, M. Kusakabe, and M. K. Cheoun, *The viability of the 3+1 neutrino model in the supernova neutrino process*, [hep-ph/1910.04984].

[13] H. Päs, h, S. Pakvasa, and T. J. Weiler, *Sterile-active neutrino oscillations and shortcuts in the extra dimension*, Phys. Rev. D **72**, 095017, [hep-ph/0504096].

[14] G. H. Collin, C. A. Argüelles, J. M. Conrad, and M. H. Shaevitz, *First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino*, Phys. Rev. Lett. **117**. no. 22, 221801, [hep-ph/1607.00011].

[15] P. Binétruy, C. Deffayet, U. Ellwanger, and D. Langlois, *Brane cosmological evolution in a bulk with cosmological constant*, Phys. Lett. B **477**, 285, [hep-th:9910219].

[16] R. Barbieri and A. Dolgov, *Bounds on sterile neutrinos from nucleosynthesis*, Phys. Lett. B **237**, 440.

[17] R. Barbieri and A. Dolgov, *Neutrino oscillations in the early universe*, Nucl. Phys. B **349**, 743.

[18] K. Enqvist, K. Kainulainen and M. J. Thomson, *Stringent cosmological bounds on inert neutrino mixing*, Nucl. Phys. B **373**, 498.

[19] M. Kusakabe, A. B. Balantekin, T. Kajino and Y. Pehlivan, *Big-bang nucleosynthesis limit on the neutral fermion decays into neutrinos*, Phys. Rev. D **87**, 085045, [astro-ph.CO/1303.2291].

[20] H. Ishida, M. Kusakabe and H. Okada, *Effects of Long-lived 10 MeV Scale Sterile Neutrino on Primordial Elemental Abundances and Effective Neutrino Number*, Phys. Rev. D **90** 083519, [astro-ph.CO/1403.5995].

[21] M. Kusakabe *et al.*, *Supernova Neutrino Process of Li and B Revisited*, Astrophys. J **872** 164, [astro-ph.HE/1901.01715].

[22] K. A. Olive *et al.* [Particle Data Group], *Review of Particle Physics*, Chin. Phys. C **38**, 090001.

[23] G. J. Mathews and T. Kajino and W. Aoki and W. Fujiya and J. B. Pitts, *Exploring the Neutrino Mass Hierarchy Probability with Meteoritic Supernova Material, ν-Process Nucleosynthesis, and θ_{13} Mixing*, Phys. Rev. D. **85**, 105023 [astro-ph.HE/1108.0725].