

COSMIC NEUTRINO FROM THE DECAY OF THE SCALARON DARK MATTER

The scalaron dark mater in $F(R)$ gravity theory can decay into pairs of massive neutrino. We calculate the corresponding decay width and the current neutrino abundance and spectrum in the universe. The obtained neutrino flux turns out to be very small compared to the solar neutrino flux at Earth at similar energies.

Keywords: *modified gravity, dark matter, neutrino.*

Introduction. The metric $F(R)$ gravity model is described by the Lagrangian

$$L_s = \frac{M^2}{3} \left(-2\Lambda + R + \frac{R^2}{6m^2} + \dots \right) = \frac{M^2}{3} F(R), \quad (1)$$

where $M = 3 \times 10^{18}$ GeV is the reduced Planck mass, Λ is the cosmological constant, and R is the scalar curvature. The constant m becomes the mass of the new degree of freedom – the scalaron. The scalaron can be a dark-matter candidate if its mass lies in the range [1–4]

$$4.4 \text{ meV} \leq m \leq 1.2 \text{ MeV}. \quad (2)$$

The upper bound is obtained from the consideration of production of electron-positron pairs in the Galactic Centre [1, 2], while the lower bound is caused by the scalaron excitation during the electroweak phase transition [3, 4]. Minimal coupling of the matter fields to $F(R)$ gravity generates universal couplings of the scalaron to all massive particles, including neutrinos. If the scalaron is sufficiently light, then it can decay only to photons and to light neutrinos. Scalaron decays into a pair of photons were under consideration, e.g., in [1–4], with the resulting lifetime

$$\tau_{\phi \rightarrow \gamma\gamma} \sim \frac{10^2 M^2}{\alpha^2 m^3} \sim 10^{38} \left(\frac{\text{eV}}{m} \right)^3 \text{ yr}, \quad (3)$$

where $\alpha \approx 1/137$ is the electromagnetic coupling constant.

According to modern experiments, at least two of the light neutrinos are massive, with the direct experimental upper bound on the mass $m_\nu < 0.8$ eV [5]. Indirect cosmological bounds are even more stringent: $\sum m_\nu < 0.12$ eV [6]. On the other hand, results on neutrino oscillations [7] give a lower bound on one of the massive light neutrinos $m_\nu > 0.05$ eV. If the scalaron dark matter is heavier than neutrino, it can decay into a neutrino-antineutrino pair. In this paper, we calculate the decay lifetime and the resulting cosmological abundance and spectrum of neutrinos from such decays.

The scalaron coupling to neutrinos and decay rate. As shown in detail in [3, 4], the scalaron interacts universally with the fields of the Standard Model through its mixing with the Higgs boson. In particular the scalaron is coupled to neutrino with a small Yukawa coupling $\lambda = m_\nu/M$ in accordance with the scalaron universal interaction with fermions (see [4]). The scalaron in the neighbourhood of the minimum of its potential is described by a massive scalar ϕ . Neutrinos (light as well as heavy) in most of the neutrino extensions of the Standard Model are of Majorana type. Therefore, we can consider the scalaron-neutrino coupling in the form

$$L_{\text{int}} = -\frac{\lambda}{2} \bar{\psi} \psi, \quad \lambda = \frac{m_\nu}{M}. \quad (4)$$

Coupling (4) in the first order gives the total decay width into a neutrino pair:

$$\Gamma = \frac{\lambda^2}{16\pi} \sqrt{m^2 - (2m_\nu)^2}. \quad (5)$$

For $2m_\nu \ll m$, this results in the lifetime with respect to such decays

$$\tau_{\phi \rightarrow \nu\bar{\nu}} \approx \frac{16\pi M^2}{mm_\nu^2} \sim 10^{40} \left(\frac{\text{eV}}{m} \right) \left(\frac{\text{meV}}{m_\nu} \right)^2 \text{ yr}. \quad (6)$$

This should be compared with (3). Given the upper bound on the neutrino mass $m_\nu < 0.8$ eV, one can observe that decays into photons will dominate for all reasonable masses of the scalaron.

Spectrum of cosmological neutrinos. Let us now calculate the current spectrum of neutrinos that were radiated by the scalaron through all the history of the expanding universe. Let $f(p)dp$ be the comoving number density of the produced neutrinos with comoving absolute momentum p in the interval dp . After neutrino with comoving momentum p are produced, this quantity remains to be constant in the homogeneous universe. During neutrino production, the quantum states with momenta p are populated according to the cosmological redshift. As the scale factor a of the universe expansion increases by Δa , the comoving momentum interval $\Delta p = p \Delta a/a$ becomes filled with particles, where p is the momentum in resonance with the oscillating scalaron. We, therefore, have

$$f(p) \Delta p = f(p) p \frac{\Delta a}{a}. \quad (7)$$

Dividing this by the corresponding time interval Δt and denoting by H the Hubble parameter, we then have

$$\frac{dn_\nu}{dt} = f(p) p H = 2\Gamma n_\phi. \quad (8)$$

Here, n_ν is the total comoving number density of neutrinos, and n_ϕ is the comoving number density of the scalaron particles, which is constant in time if their decays are neglected. This gives us the spectral distribution

$$f(p) = \frac{2\Gamma n_\phi}{H_p p}, \tag{9}$$

where H_p is the Hubble parameter at the time when neutrino with comoving momentum p is in resonance with the scalaron, i.e., when its energy $E(p/a) = m/2$ (we set the present scale factor $a_0 = 1$). From this last condition, we obtain

$$a^2 = \frac{p^2}{m^2/4 - m_\nu^2}, \quad 1+z = \frac{1}{a} = \frac{\sqrt{m^2/4 - m_\nu^2}}{p}, \tag{10}$$

where z is the cosmological redshift.

At the late time of the universe evolution, we have, approximately,

$$H = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}, \tag{11}$$

where Omegas denote the standard cosmological density parameters for matter density and cosmological constant. Substituting everything into (9), we obtain

$$f(p) = \frac{2\Gamma n_\phi}{p H_0 \sqrt{\Omega_m (m^2/4 - m_\nu^2)^{3/2} / p^3 + \Omega_\Lambda}} = \frac{\lambda^2 \rho_\phi \sqrt{1 - (2m_\nu/m)^2}}{8\pi p H_0 \sqrt{\Omega_m (m/2p)^3 (1 - (2m_\nu/m)^2)^{3/2} + \Omega_\Lambda}}, \tag{12}$$

where ρ_ϕ is the comoving energy density of the scalaron (equal to its current energy density).

For a reasonable simplicity, we will assume in what follows that $2m_\nu \ll m$. In this case, expression (12) simplifies to

$$f(p) = \frac{\lambda^2 \rho_\phi}{8\pi p H_0 \sqrt{\Omega_m (m/2p)^3 + \Omega_\Lambda}}. \tag{13}$$

Since the integral over p is convergent at the low- p end, the total number density of neutrino can be estimated as

$$n_\nu \approx \frac{\lambda^2 \rho_\phi}{8\pi H_0} \int \frac{dp}{p \sqrt{\Omega_m (m/2p)^3 + \Omega_\Lambda}} = \frac{\lambda^2 \rho_\phi}{8\pi H_0} \int \frac{dx}{x \sqrt{\Omega_m / x^3 + \Omega_\Lambda}}. \tag{14}$$

Using the relation $\Omega_\Lambda = 1 - \Omega_m$, we obtain

$$n_\nu = \frac{\lambda^2 \rho_\phi}{8\pi H_0} \times \frac{2 \operatorname{arsinh} \sqrt{1/\Omega_m - 1}}{3\sqrt{1 - \Omega_m}}. \tag{15}$$

The second factor in this expression is approximately equal to unity for the established value of $\Omega_m \approx 0.29$ [6]. We further have

$$\rho_\phi = 2M^2 H_0^2 \Omega_\phi, \tag{16}$$

hence

$$n_\nu \approx \frac{\lambda^2}{4\pi} M^2 H_0 \Omega_\phi = \frac{1}{4\pi} m_\nu^2 H_0 \Omega_\phi = 10^{-27} \left(\frac{m_\nu}{\text{meV}} \right)^2 \text{ cm}^{-3}, \tag{17}$$

where we have substituted the established values [6] for the Λ CDM model parameters $H_0 \approx 70$ km/s Mpc and $\Omega_\phi \approx 0.24$ (which is the dark-matter density parameter in our case). The spectral density (13) can then be written as

$$f(p) \approx \frac{n_\nu}{p \sqrt{\Omega_m (m/2p)^3 + 1 - \Omega_m}}, \tag{18}$$

with n_ν given by (17). This completes the determination of the spectral density of cosmological neutrinos obtained from the scalaron decays. The normalised spectral distribution $mf(p)/2n_\nu$ for $\Omega_m \approx 0.29$ is presented in Fig. 1.

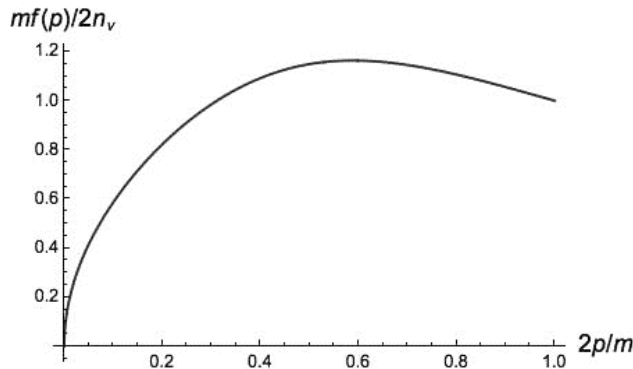


Fig. 1. Normalised spectral distribution $mf(p)/2n_\nu$ given by (18) for $\Omega_m \approx 0.29$

Discussion. We have calculated the total decay width (5) of the scalaron of mass m into a pair of Majorana neutrinos with mass m_ν . For typical realistic values of these parameters, this decay width is smaller compared to that of scalaron decay into a pair of photons, so that the corresponding lifetime (6) is larger than (3). If the scalaron forms all of dark matter in the universe, neutrinos are emitted continuously and their resulting spectral distribution is given by (12)–(18). The spectrum is broadly distributed between $p = 0$ and $p \approx m/2$ with peak around $p \approx 0.3m$ (see Fig. 1). The flux of neutrinos produced by the scalaron dark matter will be given by

$$cf(p_{\max}) \approx \frac{2cn_\nu}{m} \approx 10^{-16} \left(\frac{\text{eV}}{m} \right) \left(\frac{m_\nu}{\text{meV}} \right)^2 \text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1}. \quad (19)$$

For comparison, typical solar neutrino fluxes at Earth in the range from eV to MeV are of the order $1\text{--}10^6 \text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1}$ [8]. Since the scalaron mass in this scenario is limited by (2), we are dealing with relatively low-energy neutrinos with a small flux, hard to be detectable in the nearest future. The issue of neutrino emission from virialised dark-matter halos requires separate investigation, but the smallness of the decay width (5) will also result in low intensity of the neutrino emission line.

Acknowledgment. This research was funded by the Taras Shevchenko National University of Kyiv under project 22BF023-01.

References

1. Cembranos J. A. R. Dark matter from R^2 gravity / J. A. R. Cembranos // Phys. Rev. Lett. – 2009. – V. 102, Id. 141301.
2. Cembranos J. A. R. Modified gravity and dark matter / J. A. R. Cembranos // J. Phys. Conf. Ser. – 2016. – V. 718, Id. 032004.
3. Shtanov Yu. Light scalaron as dark matter / Yu. Shtanov // Phys. Lett. B – 2021. – V. 820, Id. 136469.
4. Shtanov Yu. Initial conditions for the scalaron dark matter / Yu. Shtanov // J. Cosmol. Astropart. Phys. – 2022. – V. 10, Id. 079.
5. The KATRIN Collaboration. Direct neutrino-mass measurement with sub-electronvolt sensitivity / The KATRIN Collaboration // Nature Physics – 2022. – V. 18, pp. 160–166.
6. The Planck Collaboration. Planck 2018 results. VI. Cosmological parameters / Astron. Astrophys. – 2020. – V. 641, Id. A6.
7. de Salas P. F. Status of neutrino oscillations 2018: 3σ hint for normal mass ordering and improved CP sensitivity / P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tórtola, J. W. F. Valle // Phys. Lett. B – 2018. – V. 782, pp. 633–640.
8. Vitagliano E. Grand unified neutrino spectrum at Earth: Sources and spectral components / E. Vitagliano, I. Tamborra, G. Raffelt // Rev. Mod. Phys. – 2020. – V. 92. – No. 4, Id. 045006.

Надійшла до редколегії 31.10.22

Ю. Штанов, д-р фіз.-мат. наук

Інститут теоретичної фізики імені М. М. Боголюбова НАН України, Київ, Україна,
Київський національний університет імені Тараса Шевченка, Київ, Україна

КОСМІЧНІ НЕЙТРИНО ВІД РОЗПАДУ СКАЛЯРОНА ЯК ТЕМНОЇ МАТЕРІЇ

Темна матерія у вигляді скалярона $F(R)$ гравітації може розпадатись на пари масивних нейтрино. Ми обчислюємо відповідну ширину розпаду та сучасну кількість і спектр таких нейтрино у Всесвіті. Отриманий потік нейтрино виявляється дуже малим порівняно з потоком сонячних нейтрино біля Землі на тих самих енергіях.

Ключові слова: модифікована гравітація, темна матерія, нейтрино.