Physics Letters B 771 (2017) 199–205

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Embedding cosmological inflation, axion dark matter and seesaw mechanism in a 3-3-1 gauge model

J.G. Ferreira Jr., C.A. de S. Pires *, J.G. Rodrigues, P.S. Rodrigues da Silva

Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, 58051-970, João Pessoa, PB, Brazil

ARTICLE INFO

Article history:
Received 25 March 2017
Received in revised form 9 May 2017
Accepted 10 May 2017
Available online 19 May 2017
Editor: M. Trodden

ABSTRACT

The Peccei–Quinn symmetry is an intrinsic global symmetry of the 3-3-1 gauge models. Its spontaneous breaking mechanism engendering an invisible KSVZ-like axion links the 3-3-1 models with new physics at $\sim 10^{10}$ GeV scale. The axion that results from this mechanism is an interesting candidate for the dark matter of the universe, while its real partner may drive inflation if radiative corrections are taken into account. This is obtained by connecting the type I seesaw mechanism with the spontaneous breaking of the Peccei–Quinn symmetry. In the end of the day we have a scenario providing a common answer to the strong-CP problem, inflation, dark matter and neutrino mass.

1. Introduction

The $SU(3)_C \times SU(3)_L \times U(1)_N$ (3-3-1) gauge models for the electroweak interactions are interesting in their own right. For example, in these models generation cannot replicate unrestrictedly as in the standard model (SM), since it is not exact replica of one another and each is separately anomalous. However, when three generations are taken into account, gauge anomaly is automatically canceled [1,2], providing a reason for the existence of three families of fermions.

Moreover, the set of constraints provided by the gauge invariance of the Yukawa interactions together with those coming from the anomaly cancellation conditions are enough to fix the electric charges of the particles in the 3-3-1 model, thus providing an understanding of the pattern of electric charge quantization [3,4].

In what concerns the Peccei–Quinn (PQ) symmetry, it is an automatic symmetry of these models, thus elegantly solving the strong CP-problem [5]. However, the original versions of the 3-3-1 gauge models furnish an unrealistic axion because of its sizable couplings with the standard particles [6,7]. In order to have an invisible axion a neutral scalar singlet must be added to the conventional scalar sector [8–11].

Regarding neutrino masses, canonical seesaw mechanisms, as type I and type II, as well as the inverse seesaw mechanism are easily implemented in the framework of the 3-3-1 models [12–16].

From the phenomenological point of view, a remarkable aspect of the 3-3-1 models relies on flavor physics. Rare decays, lepton number violation and flavor changing neutral current are natural outcome of the model [17–24]. Recent collider phenomenology of these models are performed in Refs. [25–27].

Last in the sequence but not least in importance, we remember that conventional particle content of some 3-3-1 models includes a stable and neutral particle that may play the role of cold dark matter in the WIMP form [28–31]. These interesting features turn the 3-3-1 models an appealing candidates for physics beyond the SM. In this point we call the attention to the fact that the physics of the early universe, particularly inflation, has been poorly explored within these models [32,33]. Thus, in view of the recent experimental advances in probing inflation observables, it turns imperative to search for mechanisms that allow implementation of inflation in the framework of the 3-3-1 gauge models.

Concerning implementation of cosmological issues within phenomenological gauge models, as the SM, we remark that there are two distinct ways of providing a common solution to cosmological inflation, cold dark mater and neutrino masses within the SM. The first arises within the type I seesaw mechanism for small neutrino masses. By adding right handed neutrinos and at least one neutral scalar in the singlet form to the SM, besides considering spontaneous breaking of global lepton number within type I seesaw mechanism, one has that the real part of the neutral singlet may drive inflation while the imaginary part may be the dark matter of the universe [34,35].

On the other hand, the implementation of the PQ symmetry in the standard model may be accomplished by adding exotic vector

* Corresponding author.
E-mail address: cpires@fisica.ufpb.br (C.A. de S. Pires).

http://dx.doi.org/10.1016/j.physletb.2017.05.034

like quarks, right-handed neutrinos and neutral scalar singlet to its particle content. This scenario is called SMASH [36–40]. The PQ symmetry is spontaneously broken when the neutral scalar singlet develops vacuum expectation value (VEV) different from zero. In this circumstance, the imaginary part of this scalar singlet will be the invisible axion, which may play the role of dark matter, while the real part may drive inflation. Moreover, on coupling the neutral scalar singlet to the right-handed neutrino, through an Yukawa interaction, the VEV of the neutral scalar, that must lie in the range (10^{10}–10^{11}) GeV, will generate mass to heavy neutrinos that may trigger the type I seesaw mechanism yielding small masses for the standard neutrinos. The problem with this scenario is that it generates an inflaton potential of the type $\lambda\phi^4$ which is practically excluded by the current bounds from PLANCK15 [41]. A way of circumventing such a problem is, either to consider that the inflaton couples non-minimally with the scalar curvature R, or take into account radiative corrections to the inflaton potential.

The main difference among these two proposals relies on the dark matter sector. In the former case the dark matter candidate, a Majoron, gains mass from quantum gravity effect and then is classified as warm dark matter, while in the latter case the dark matter candidate is the axion and is classified as cold dark matter candidate. The axion gains mass from QCD and quantum gravity effects. Care must be taken because quantum gravity effect may destabilize the axion as dark matter candidate. We take care of this by means of large discrete symmetry.

Since the PQ symmetry is an automatic symmetry of the 3-3-1 gauge models, consequently its version involving right-handed neutrinos realizes automatically the SMASH proposal. In this case it turns imperative to check if the real partner of the axion will drive inflation. We show that this is possible when radiative corrections are taken into account. We examine also reheating phase. It is engendered by the decay of the inflaton into the conventional scalars. The model easily provides a reheating temperature of 10^9 GeV for typical values of the parameters required by canonical inflation models. In addition, standard neutrinos will gain mass through the type I seesaw mechanism and the axion is the natural dark matter candidate of the model.

The paper is divided in the following way: In Sec. 2 we revisit the 3-3-1 model that contains an invisible axion in its spectrum. Next, in Sec. 3, we develop the inflationary paradigm in such model. We finally conclude in Sec. 4.

2. The 3-3-1 model, the Peccei–Quinn symmetry and the invisible axion

The model developed here is one proposed in Ref. [42] which is a modification of the original one [1,43,44]. To realize our proposal, heavy neutrinos in the singlet form must be added to the leptonic sector of the model

$$f_L^a = \begin{pmatrix} \nu_L^a \\ e_L^a \\ (\nu_R^c)^a \end{pmatrix} \sim (1\,,\,3\,,\,-1/3)\,,\;\; e_{aR} \sim (1,1,-1)\,,$$
$$N_{aR} \sim (1,1,0) \tag{1}$$

with $a = 1, 2, 3$ representing the three known generations. We are indicating the transformation under 3-3-1 after the similarity sign, "$\sim$".

The quark sector is kept intact with one generation of left-handed fields coming in the triplet fundamental representation of $SU(3)_L$ and the other two composing an anti-triplet representation with the content

$$Q_{iL} = \begin{pmatrix} d_{iL} \\ -u_{iL} \\ d'_{iL} \end{pmatrix} \sim (3\,,\,\bar{3}\,,\,0)\,,\quad Q_{3L} = \begin{pmatrix} u_{3L} \\ d_{3L} \\ u'_{3L} \end{pmatrix} \sim (3\,,\,3\,,\,1/3)\,, \tag{2}$$

and the right-handed fields

$$u_{iR} \sim (3,1,2/3)\,,\, d_{iR} \sim (3,1,-1/3)\,,\, d'_{iR} \sim (3,1,-1/3)$$
$$u_{3R} \sim (3,1,2/3)\,,\, d_{3R} \sim (3,1,-1/3)\,,\, u'_{3R} \sim (3,1,2/3), \tag{3}$$

where $j = 1, 2$ represent different generations. The primed quarks are the exotic ones but with the usual electric charges.

In order to generate the masses for the gauge bosons and fermions, the model requires only three Higgs scalar triplets. For our proposal here we add a neutral scalar in the singlet form such that the scalar content is composed by

$$\chi = \begin{pmatrix} \chi^0 \\ \chi^- \\ \chi'^0 \end{pmatrix} \sim (1\,,\,3\,,\,-1/3)\,,\;\; \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta'^0 \end{pmatrix} \sim (1\,,\,3\,,\,-1/3),$$
$$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho'^+ \end{pmatrix} \sim (1\,,\,3\,,\,2/3)\,,\quad \phi \sim (1,1,0). \tag{4}$$

Thus the particle content of the model in Ref. [42] is extended by the fields N_{a_R} and ϕ.

In order to keep intact the physics results of the Ref. [42], the Lagrangian of the model must be invariant by the following set of discrete symmetries $Z_{11} \otimes Z_2$ but now with Z_{11} acting as

$$\begin{aligned}
&\phi \to \omega_1^{-1}\phi\,, && f_{aL} \to \omega_1 f_{aL}\,,\\
&\rho \to \omega_2^{-1}\rho\,, && d_{aR} \to \omega_2 d_{aR}\,,\\
&\chi \to \omega_3^{-1}\chi\,, && u'_{3R} \to \omega_3 u'_{3R}\,,\\
&Q_{iL} \to \omega_4^{-1}Q_{iL}\,, && d'_{iR} \to \omega_4 d'_{iR}\,,\\
&\eta \to \omega_5^{-1}\eta\,, && u_{aR} \to \omega_5 u_{aR}\,,\\
&Q_{3L} \to \omega_0 Q_{3L}\,, && N_R \to \omega_5^{-1}N_R\,,\\
&e_{aR} \to \omega_3 e_{aR}\,,
\end{aligned} \tag{5}$$

where $\omega_k \equiv e^{2\pi i \frac{k}{11}}$, $\{k = 0, \pm 1, ..., \pm 5\}$.

The Z_2 symmetry must act as

$$(\rho\,,\chi\,,d'_R\,,u'_{3R}\,,u_R\,,d_R\,,e_R) \;\to\; -(\rho\,,\chi\,,d'_R\,,u'_{3R}\,,u_R\,,d_R\,,e_R)\,. \tag{6}$$

These discrete symmetries yield the following Yukawa couplings

$$\begin{aligned}
\mathcal{L}^Y =\; & G_1\bar{Q}_{3L}u'_{3R}\chi + G_2^{ij}\bar{Q}_{iL}d'_{jR}\chi^* + G_3^{3a}\bar{Q}_{3L}u_{aR}\eta + G_4^{ia}\bar{Q}_{iL}d_{aR}\eta^*\\
& + G_5^{3a}\bar{Q}_{3L}d_{aR}\rho + G_6^{ia}\bar{Q}_{iL}u_{aR}\rho^* + g_{ab}\bar{f}_{aL}e_{bR}\rho\\
& + h_{ab}\bar{f}_{aL}\eta N_{bR} + h'_{ab}\phi\bar{N}_{aR}^C N_{bR} + \text{H.c.}
\end{aligned} \tag{7}$$

The transformations displayed in Eqs. (5) and (6) are a little different from the original case [42]. The reason for this is to accommodate the last two terms in the Lagrangian above which are crucial for our proposal, as we will see later. The physics of the original case remains the same because the new terms involve heavy neutrinos that are standard model singlets.

The potential does not change. It is exactly the same as in the original case, i.e.,