Physics Letters B 757 (2016) 399–404

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

A critical analysis of one-loop neutrino mass models with minimal dark matter

Amine Ahriche [a,b], Kristian L. McDonald [c,*], Salah Nasri [d], Ivica Picek [e]

[a] Laboratory of Mathematical and Sub-Atomic Physics (LPMPS), University of Constantine I, DZ-25000 Constantine, Algeria
[b] The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, I-34014, Trieste, Italy
[c] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, NSW 2006, Australia
[d] Physics Department, UAE University, POB 17551, Al Ain, United Arab Emirates
[e] Department of Physics, Faculty of Science, University of Zagreb, P.O.B. 331, HR-10002 Zagreb, Croatia

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form 8 April 2016
Accepted 9 April 2016
Available online 13 April 2016
Editor: J. Hisano

ABSTRACT

A recent paper investigated minimal RνMDM models with the type T1-iii and T3 one-loop topologies. However, the candidate most-minimal model does not possess an accidental symmetry – the scalar potential contains an explicit symmetry breaking term, rendering the dark matter unstable. We present two models that cure this problem. However, we further show that *all* of the proposed minimal one-loop RνMDM models suffer from a second problem – an additional source of explicit Z_2 symmetry breaking in the Yukawa sector. We perform a more-general analysis to show that neutrino mass models using either the type T3 or type T1-iii one-loop topologies do not give viable minimal dark matter candidates. Consequently, one-loop models of neutrino mass with minimal dark matter do not appear possible. Thus, presently there remains a single known (three-loop) model of neutrino mass that gives stable dark matter without invoking any new symmetries.

1. Introduction

The origin of neutrino mass and the particle physics properties of dark matter (DM) constitute two important unsolved problems in particle physics research. While it is a logical possibility that these problems possess independent solutions, it is interesting to consider the alternative – that they admit a common or unified solution. This was the approach advocated by Krauss, Nasri and Trodden [1] and also by Ma [2]; both groups presented models in which neutrino mass appears as a radiative effect due to interactions with a Z_2-odd sector that contains a stable DM candidate. The former (latter) advocated a three-loop (one-loop) model of neutrino mass. More generally there has been a great deal of research in this area; for related early works see Ref. [3], while for more recent models see e.g., Ref. [4] and references therein.

In the Standard Model (SM) proton stability results from an accidental (baryon number) symmetry. It is natural to ask whether DM stability could similarly result from an accidental symmetry. This approach, dubbed Minimal DM [5], is well studied in the literature. In the context of the SM, it is well known that an accidentally-stable DM candidate arises if the SM is extended to include either a hypercharge-less quintuplet fermion multiplet, $\mathcal{F}\sim(1,5,0)$, or a septuplet scalar multiplet, $\phi\sim(1,7,0)$ [5]. Note that the Minimal DM framework does not hold for a scalar multiplet $\phi\sim(1,5,0)$, as the Z_2 symmetry is explicitly broken [5].

The notion of Minimal DM was first applied to radiative neutrino mass models in Ref. [6], the goal being to extend the SM with new particles that generate radiative neutrino mass while also giving an accidental symmetry to achieve a stable DM candidate (the model was dubbed RνMDM). Unfortunately it was subsequently shown that the model did not work, due to a symmetry-breaking term in the scalar potential [7]. More recently a three-loop model of neutrino mass was proposed in which DM stability resulted from an accidental symmetry (without invoking any beyond-SM symmetries) [8]. This appears to be the first viable model to achieve accidental DM in the context of a radiative neutrino mass model, the DM being a septuplet fermion, $\mathcal{F}\sim(1,7,0)$, in this instance. There also exists a three-loop model of neutrino mass [9] that employs both minimal DM candidates identified in Ref. [5].

* Corresponding author.
E-mail addresses: aahriche@ictp.it (A. Ahriche), kristian.mcdonald@sydney.edu.au (K.L. McDonald), snasri@uaeu.ac.ae (S. Nasri), picek@phy.hr (I. Picek).

http://dx.doi.org/10.1016/j.physletb.2016.04.022

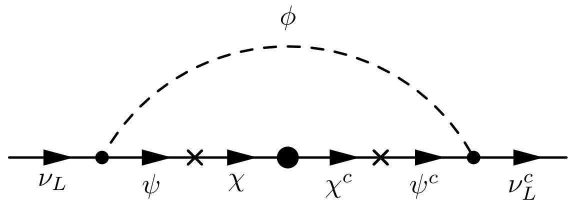

Fig. 1. One-loop diagram for neutrino mass with the type T1-iii topology. Crosses denote insertions of the SM Higgs vacuum value and the larger dot denotes a Majorana mass insertion for the real fermion χ.

Motivated by a recent study of one-loop models for neutrino mass with minimal DM [10], we perform a general analysis of one-loop models. In particular, we show that neutrino mass models using either the type T3 or type T1-iii one-loop topologies [11] do not give viable (i.e. accidentally stable) minimal DM candidates, due to explicit breaking of the requisite symmetry. Furthermore, our results indicate that it is not possible to obtain minimal DM by the use of one-loop neutrino mass models.

The layout of this paper is as follows. In Section 2 we demonstrate the presence of explicit Z_2 symmetry breaking in the scalar potential of the minimal one-loop model identified in Ref. [10], presenting two new models that cure this problem. In Section 3 we perform a critical analysis of models with the type T3 one-loop topology. Similarly, we study models with the type T1-iii topology in detail in Section 4. Conclusions are drawn in Section 5.

2. Symmetry breaking in the scalar potential for type T1-iii one-loop models

A recent work has reconsidered the RνMDM approach, attempting to find one-loop neutrino mass models with accidentally stable DM candidates [10]. Three models were identified as candidates; two employing the so-called T1-iii one-loop topology [11], with the beyond-SM particle content being (see Table 1 in Ref. [10])[1]

$$\begin{aligned}\text{Model A}: \quad & \chi \sim (1,7,0), \quad \psi \sim (1,6,1), \\ & \bar{\psi} \sim (1,6,-1), \quad \phi \sim (1,5,0), \end{aligned} \tag{1}$$

$$\begin{aligned}\text{Model B}: \quad & \chi \sim (1,5,0), \quad \psi \sim (1,4,1), \\ & \bar{\psi} \sim (1,4,-1), \quad \phi \sim (1,5,0), \end{aligned} \tag{2}$$

where χ, ψ, and $\bar{\psi}$ are fermions while ϕ is a scalar multiplet (the type T1-iii one-loop diagram for these models is shown in Fig. 1). The models are purportedly invariant under an accidental Z_2 symmetry, where χ, ψ, $\bar{\psi}$ and ϕ are Z_2-odd, while the SM fields are Z_2-even; it is clear from Fig. 1 that this is an accidental symmetry of the loop diagram. One further model, employing the so-called T3 one-loop topology was also proposed. Ref. [10] then performed a detailed study of the T1-iii one-loop model with particle content in Eq. (2), namely Model B.

With regard to Models A and B in Eqs. (1) and (2), we note that the most-general Lagrangian obtained by adding $\phi \sim (1,5,0)$ to the SM contains the term $\mu\phi^3$, which explicitly breaks any Z_2 symmetry under which ϕ is odd-valued. This point is understood by the absence of a scalar quintuplet Minimal DM candidate in Ref. [5]. For completeness, however, we note that, after writing the scalar quintuplet in symmetric-tensor notation as ϕ_{abcd}, where the $SU(2)$ indices take values $a, b, \ldots = 1, 2$, the cubic term $\mu\, \phi_{abcd}\, \phi_{efgh}\, \epsilon^{cg}\, \epsilon^{dh}\, (\phi^*)^{abef}$ appears in the most-general scalar potential (here μ denotes the coupling). This conclusion holds when additional fields are added to the model. Thus, Model B, defined by Eq. (2) and studied in detail in Ref. [10], contains an explicit source of Z_2 symmetry breaking and the DM candidate is unstable.

Here we wish to emphasize that a viable one-loop model for Minimal DM and radiative neutrino mass via the T1-iii topology is obtained if one modifies Model B by promoting the field content as follows[2]:

$$\begin{aligned}\text{Model C}: \quad & \chi \sim (1,5,0), \quad \psi \sim (1,6,1), \\ & \bar{\psi} \sim (1,6,-1), \quad \phi \sim (1,7,0). \end{aligned} \tag{3}$$

This model appears particularly interesting as it contains two DM candidates, namely the quintuplet fermion, $\chi \sim (1,5,0)$, and the septuplet scalar, $\phi \sim (1,7,0)$, both of which were identified as Minimal DM candidates in Ref. [5]. Depending on the mass ordering of χ and ϕ, it appears that either fermionic or scalar DM is possible (or possibly both in a near degenerate case). Importantly, the model does not contain the cubic term ϕ^3 in the scalar potential.

With regards to Model A, we suspect that Table 1 in Ref. [10] (i.e. Eqs. (1) and (2) above) contains a minor typographical error, in which the scalar ϕ should instead be a septuplet, $\phi \sim (1,5,0) \rightarrow \phi \sim (1,7,0)$. If this is correct, the scalar potential for Model A preserves the accidental symmetry of the loop diagram, though, unlike Model B, this model was not studied in detail. It is important to emphasize, however, that this model contains two DM candidates, both a fermionic DM candidate, in the form of the septuplet $\chi \sim (1,7,0)$ [8] and a scalar DM candidate, in the form of $\phi \sim (1,7,0)$. According to the criterion of minimality employed in Ref. [10], it appears that Model C in Eq. (3) would be considered more minimal, due to the smaller $SU(2)$ representations involved.

We also note that a related model is obtained by promoting the fermions ψ in Model A to octuplets:

$$\begin{aligned}\text{Model D}: \quad & \chi \sim (1,7,0), \quad \psi \sim (1,8,1), \\ & \bar{\psi} \sim (1,8,-1), \quad \phi \sim (1,7,0). \end{aligned} \tag{4}$$

This model may also be an interesting variant as it contains two distinct DM candidates, namely the fermion $\chi \sim (1,7,0)$ and the scalar $\phi \sim (1,7,0)$, though Model C would be considered more minimal.

In summary, we find the following minimal models of one-loop neutrino mass via the T1-iii topology in which the accidental symmetry of the one-loop diagram is preserved by the scalar potential:

$$\begin{aligned}\text{Model I}: \quad & \chi \sim (1,5,0), \quad \psi \sim (1,6,1), \\ & \bar{\psi} \sim (1,6,-1), \quad \phi \sim (1,7,0), \\ \text{Model II}: \quad & \chi \sim (1,7,0), \quad \psi \sim (1,6,1), \\ & \bar{\psi} \sim (1,6,-1), \quad \phi \sim (1,7,0). \\ \text{Model III}: \quad & \chi \sim (1,7,0), \quad \psi \sim (1,8,1), \\ & \bar{\psi} \sim (1,8,-1), \quad \phi \sim (1,7,0), \end{aligned} \tag{5}$$

where Model II appears in Ref. [10] and Models I and III are new. The new Model I contains both Minimal DM candidates identified in Ref. [5], namely the fermion $\chi \sim (1,5,0)$ and the scalar $\phi \sim (1,7,0)$, and could give either fermionic or scalar DM. None of these models possess the cubic term ϕ^3, so the accidental symmetry of the loop diagram is preserved by the scalar potential. We note that, due to the fact that the quintuplet and septuplet DM

[1] See the Note Added at the end of the paper. Also, note that our hypercharge normalization differs by a factor of 2.

[2] Note that the term $\mu\phi^3$ is not allowed for a septuplet scalar, unlike the quintuplet case of Model B.