Title
Alternatives to Seesaw

Permalink
https://escholarship.org/uc/item/16w9170g

Author
Murayama, Hitoshi

Publication Date
2009-09-18
Alternatives to Seesaw

Hitoshi Murayama

School of Natural Sciences, Institute for Advanced Study
Princeton, NJ 08540, USA

and

Lawrence Berkeley National Laboratory
and University of California
Berkeley, CA 94720, USA

This work was supported in part by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.
Alternatives to Seesaw

Hitoshi Murayama\textsuperscript{a}\footnote{On leave of absence from Department of Physics, University of California, Berkeley, CA 94720.}

\textsuperscript{a}School of Natural Sciences, Institute for Advanced Study
Princeton, NJ 08540, USA

The seesaw mechanism is attractive not only because it “explains” small neutrino mass, but also because of its packaging with the SUSY-GUT, leptogenesis, Dark Matter, and electroweak symmetry breaking. However, this package has the flavor, CP, and gravitino problems. I discuss two alternatives to the seesaw mechanism. In one of them, the anomaly-mediated supersymmetry breaking solves these problems, while predicts naturally light Dirac neutrinos. In the other, the light Majorana neutrinos arise from supersymmetry breaking with right-handed neutrinos below TeV, and the Dark Matter and collider phenomenology are significantly different.

1. Introduction

We are here to celebrate 25 years of the seesaw mechanism \cite{1}. This attractive mechanism is meant to explain why the neutrino masses are finite, yet tiny compared to all the other elementary fermion masses. Tsutomu Yanagida and Pierre Ramond in the audience pioneered this mechanism from the point of view of the $SO(10)$ grand unified theories. It predicts the mass of the right-handed neutrinos $N$ at the GUT-scale $M_R \sim M_{GUT} \gg 2 \times 10^{16}$ GeV $\gg v = 176$ GeV, and the light neutrino mass is suppressed tremendously as $m_\nu \sim v^2/M_{GUT} \simeq 1$ meV.

Actually, what most of us find attractive is not just the mechanism to suppress the neutrino mass, but rather the whole package of the grand unification \cite{2}, the supersymmetry to stabilize the hierarchy \cite{3,4,5,6,7,8,9}, the seesaw mechanism to suppress the neutrino mass, and the (thermal) leptogenesis that explains the baryon asymmetry of the universe and hence “why we exist” in terms of the out-of-equilibrium decay of the right-handed neutrinos \cite{10}. Furthermore, the whole package comes with all the usual goodies of the supersymmetry, namely the Lightest Supersymmetric Particle (LSP) as a natural candidate for the cosmological Dark Matter \cite{11,12} and radiative breaking of the electroweak symmetry \cite{13,14,15,16}, potentially connected to the superstring theory.

Why talk about alternatives then? Even though this package is compelling and attractive, it has problems. First of all, the supersymmetry comes with the flavor and CP problems due to the new particles and their flavor- and CP-violating parameters below the TeV scale (see, e.g., \cite{17}). In view of the string unification, the GUT-scale, which is supposed to explain the smallness of the neutrino mass, is put in by hand arbitrarily and is not explained. Furthermore, the proton decay had not been seen at the predicted rate and the naive SUSY-GUT appears to be in trouble \cite{18}. Concerning the cosmology, the
thermal leptogenesis requires the (lightest) right-handed neutrino mass to be $M_R \gtrsim 10^9$ GeV, and hence the reheating temperature after the inflation $T_{RH} \gtrsim 10^{10}$ GeV \cite{19}. On the other hand, the gravitinos, expected at $m_{3/2} \approx 100$–1000 GeV, are produced thermally at high temperatures and decay late, jeopardizing the success of the Big-Bang Nucleosynthesis (BBN) theory. In fact, the hadronic decays of the gravitinos cause so much trouble that the reheating temperature must be kept below $T_{RH} < \sim 10^6$ GeV \cite{26,27}. Therefore the leptogenesis and supersymmetry appear to be in conflict. Finally, the seesaw mechanism itself is very difficult to test. In particular, the thermal leptogenesis prefers neutrino mass eigenvalues $m_{\nu 1,2,3} < \sim 0.1$ eV \cite{19}, and hence the detection of the neutrinoless double beta decay is far from trivial.

Therefore I believe it is worthwhile discussing alternatives to the by-now-standard seesaw mechanism. I will discuss two such possibilities.

In the first one, the neutrino mass is suppressed by the hierarchy between the Planck-scale and the supersymmetry breaking scale. Normally this hierarchy would give a too small neutrino mass; however in the anomaly-mediated supersymmetry breaking \cite{28,29}, the superparticle masses are suppressed by loop-factors, and correspondingly the source of the supersymmetry breaking, i.e., the gravitino mass, is enhanced relative to the TeV-scale. It predicts the neutrino mass of $m_\nu \sim 100\text{TeV}/M_{Pl} \sim 10$ meV, much closer to the data of 8–50 meV \cite{30}. In addition, the anomaly-mediated supersymmetry breaking automatically solves the SUSY flavor problem. In this implementation, the neutrinos are Dirac fermions. If we are lucky, the long-baseline neutrino oscillation experiments will tell us that the neutrino spectrum is inverted, while the negative search for the neutrinoless double beta decay will set the limit $|\langle m_\nu \rangle_{ee}| < 0.01$ eV.

If this happens, we will establish the Dirac nature of neutrinos, giving a clear preference to a scenario of this type over the conventional seesaw. Despite the conserved lepton number, it is possible to have “Dirac leptogenesis” explaining the cosmic baryon asymmetry \cite{31,32}.

2. Consistent Anomaly Mediation

In this section, we present a framework where SUSY flavor and CP problems are solved, as well as the cosmological gravitino problem. The neutrinos are naturally light but Dirac, yet the leptogenesis is possible. It relies heavily on the anomaly-mediated supersymmetry breaking.

2.1. Flavor and CP Problems

It is well-known that generic supersymmetry breaking effects would induce unacceptably large flavor-changing effects as well as CP-violating effects. For example, the diagrams in Fig. 2 can induce too-large contribution to neutral kaon mixing or electron electric dipole moment (EDM). The vertices indicated by green crosses must be extremely suppressed in order to satisfy the experimental constraints, down to $10^{-4}$ of the natural size in some cases.

Many proposals exist that avoid these serious problems in supersymmetry. The popular frameworks are gauge mediation \cite{33,34,35} or gaugino mediation \cite{36,37} of supersymmetry breaking. In these frameworks, the masses and mixings of superpartners are induced by the standard-model gauge interactions, and hence are flavor neutral and do not induce flavor-changing effects. With some extra work, they can be made also real, hence CP-preserving. In both cases, the idea is to overcome the “bad” supergravity induced supersymmetry breaking effects by the “good” gauge induced effects. Namely actively trying to induce large effects is the approach.

However, the gauge mediation predicts a light gravitino, between 100 keV and 10 GeV, which has also a severe cosmological limits from the overclosure and the BBN \cite{38,39}. \footnote{Note, however, some small portions of the parameter space allow viable yet interesting cosmology of gravitino dark matter, studied recently for example in \cite{40,41,42,43}.}

Note, however, some small portions of the parameter space allow viable yet interesting cosmology of gravitino dark matter, studied recently for example in \cite{40,41,42,43}.
mediation requires a rather high energy scale for the mediation, typically above the GUT-scale, so that the slepton masses are enhanced enough by the renormalization-group running. It therefore leaves the concern that some flavor physics below the mediation scale, such as right-handed neutrinos in the seesaw mechanism, induce flavor-dependent effects despite the initial flavor-blind boundary conditions. Moreover, neither framework seems to provide obvious connections to neutrino physics. I will not discuss them any further here.

The alternative approach is the anomaly mediation. In this framework, one actively tries not to induce supersymmetry breaking effects, by making the sector responsible for supersymmetry breaking as “sequestered” from the standard model as possible. I call this approach “Zen of supersymmetry breaking:” You try not to mediate, and you mediate good ones. One such sequestering mechanism is the physical separation of two sectors on separate points in the extra dimensions \([28]\), another is to use “conformal sequestering” motivated by the AdS/CFT correspondence \([44,45]\), where the unwanted direct coupling of the two sectors is suppressed by a near conformal dynamics of the supersymmetry breaking sector.

The point is simply that the gravity always exists. And the gravity couples to energy. All parameters in the theory that have dimensions of energy receive supersymmetry breaking effects through gravity, while dimensionless parameters do not. All parameters in the standard model except for one, namely the Higgs negative mass squared, are dimensionless, and they do not receive supersymmetry breaking effects. However, the dimensionless parameters are actually secretly dimensionful due to the running of the coupling constants. They do depend on mass scales. Because of the dependence on the mass scales, namely the conformal anomaly, the supersymmetry breaking effects appear proportional to the beta functions \(\beta_A(g_A) = \mu \frac{d}{d\mu} g_A\) of the running gauge coupling constants or the anomalous dimension factors \(\gamma_i = -\frac{1}{2} \mu \frac{d}{d\mu} \log Z_i\) which make
the Yukawa couplings run. The result is

\[
A_{ijk} = -\lambda_{ijk}(\gamma_i + \gamma_j + \gamma_k)m_{3/2} \quad (1)
\]

\[
\tilde{m}_i = \frac{1}{2} \mu \frac{d\lambda_i}{d\mu} m_{3/2}^{2} \quad (2)
\]

\[
M_A = \beta_A m_{3/2} \quad ,
\]

a consequence of the superconformal anomaly, hence the name.

The most remarkable point about this result is that it is completely “UV-insensitive.” The predictions are given in terms of the interactions at the energy scale of interest only; whatever happens at much higher energy scales does not affect the result. This is in stark contrast to other scenarios, where any physics below the scale of mediation would correct and modify the supersymmetry breaking effects at the electroweak scale through renormalization, and hence UV-sensitive. In the supersymmetric Standard Model, the only flavor-dependence appears through the Yukawa couplings, which are practically negligible for the first- and second-generation particles. Therefore the supersymmetry breaking effects are flavor-blind, except for the third-generation particles. It automatically solves the flavor problem in supersymmetry.

I cannot overemphasize how incredible the UV-insensitivity is. For example, one can verify this fact by writing down a model with extra heavy particles and carefully integrate them out later. The supersymmetry breaking effects above the mass thresholds of heavy particles are complicated and flavor-dependent, but once they are integrated out, the threshold corrections modify the low-energy supersymmetry breaking effects in such a way that they become flavor-blind [29,46].

This is the opposite from the other “flavor-blind” mediation mechanisms. They set the boundary conditions in the UV to be flavor-blind, and the flavor physics below that scale screw up the original flavor blindness. In anomaly mediation, the supersymmetry breaking effects at high energies are complicated and flavor-dependent; yet after integrating out heavy degrees of freedom, the flavor-dependence magically gets canceled out.

2.2. Gravitino Problem

The immediate gratification of anomaly mediation is the resolution of the cosmological gravitino problem. Once supersymmetry is assumed, there is a superpartner of the gravitino, the gravitino $\tilde{G}$. Its interaction is only gravitational and hence weak. Therefore its lifetime is expected to be long, $\tau_3 = \frac{m_3^2}{10^{10}}$, and typically decays after the BBN and dissociate some of the light elements already synthesized by that time. This would destroy the agreement between the BBN theory and the observed light element abundances. If the gravitinos are as populous as other particle species, it is a disaster. We have to assume that the gravitinos had been wiped out by the cosmological inflation. However the hot gas in the early universe produces gravitinos from the scattering process such as $gg \rightarrow \tilde{g}G$. Its abundance is given approximately by $n_{3/2} / s \approx 10^{-12}T_{RH}/10^{10}$ GeV, larger for the higher reheating temperature after the inflation. Therefore the success of the BBN theory places an upper limit on $T_{RH}$. In particular, when the gravitinos decay dominantly into hadrons, the constraints were found to be particularly strong [29]. The limit is shown in Fig. 4 as a function of the gravitino mass. For a TeV gravitino, the upper limit is $T_{RH} \leq 300$ TeV, making the thermal leptogenesis very difficult.

In anomaly mediation, this problem is basically solved automatically. Because the supersymmetry breaking effects are induced from the superconformal anomaly, and hence loop suppressed, the gravitino mass is enhanced relative to the superpartner masses, $m_{3/2} \approx (4\pi)^2 m_3 \approx 100$ TeV. Such a heavy gravitino makes it decay well before the BBN, making it safe. There is an additional constraint that the LSP in the decay product of the gravitinos should not overclose the universe [37],

\[
T_{RH} \leq 3 \times 10^{10} \, \text{GeV} \left( \frac{m_{LSP}}{100 \, \text{GeV}} \right) . \quad (4)
\]

Note that this is a much weaker constraint than those in Fig. 4.

2.3. Slepton Mass Problem

However, there is a serious problem with the anomaly mediation. It is too predictive! It has only one free parameter, the gravitino mass $m_{3/2}$.
Figure 4. The constraint on the reheating temperature from the compatibility of the Big-Bang Nucleosynthesis and the hadronic decay of gravitinos produced after the inflation [27].

In predicting all superpartner masses. In particular, the slepton mass-squared is predicted to be negative, breaking the electromagnetism and making the photon massive. You wouldn’t be able to see my slides! Phenomenologically, the framework is DOA: “dead on arrival.”

There had been many fixes proposed to this problem [48, 49, 50, 51, 52, 53, 54, 55, 56]. One of the simplest is to add a universal scalar mass. More elaborate one uses a “non-supersymmetric threshold,” namely a flat direction that acquires a large expectation value due to supersymmetry breaking effects. The unfortunate aspect of all these proposals is that they fix the problem by abandoning the UV insensitivity one or the other way. They are therefore not immune from the flavor problem anymore. One possibility to make the slepton masses positive without abandoning the UV insensitivity is to introduce new Yukawa interactions for leptons; within

the supersymmetric Standard Model, only such possibility is the $R$-parity violation [27], but it breaks the lepton number too much (and hence too large neutrino mass). Moreover the UV insensitivity does not guarantee the absence of the flavor problem either because the $R$-parity violating couplings are flavor-dependent. Specific choices need to be made to avoid this problem.

There is, fortunately, a simple way to make the slepton masses positive while maintaining the UV insensitivity [30], by adding $D$-term contributions to the scalar masses $m_3^2 \rightarrow m_3^2 + q_i D$ [58]. The UV insensitivity is preserved when the $U(1)$ symmetry is anomaly free with respect to the standard model gauge group [30]. In the MSSM there are two candidates of the anomaly free $U(1)$ symmetries, i.e., $U(1)_Y$ and $U(1)_{B-L}$, and those $D$-term contributions are sufficient to resolve the tachyonic slepton problem. Although $U(1)_Y$ is unbroken above the electroweak scale, the kinetic mixing between $U(1)_{B-L}$ and $U(1)_Y$ induces a $D$-term for $U(1)_Y$, once a $D$-term for $U(1)_{B-L}$ is generated.

2.4. Neutrino Mass

Now we turn our attention to the neutrino mass in this framework. In order to add the $U(1)_{B-L}$ $D$-term and maintain the UV insensitivity, $U(1)_{B-L}$ remains as a global symmetry of the theory. It then forbids the Majorana mass of neutrinos, and hence the standard seesaw mechanism cannot be used.\(^5\)

It turns out that this is not a problem but rather a virtue. Having imposed $U(1)_{B-L}$, the right-handed neutrinos $N$ must be light without their usual Majorana mass. Clearly $O(1)$ neutrino Yukawa couplings must be forbidden to avoid too heavy neutrinos. It can be done, for example, by a $U(1)_R$ symmetry with charge +2/3 for $Q$, $L$, charge +1/3 for $U$, $D$, and $E$, charge +1 for $H_u$ and $H_d$, and charge −5/3 for $N$. On

\(^5\)There is, however, a possible compromise. The standard seesaw mechanism breaks $U(1)_{B-L}$ explicitly and hence induces UV sensitivity, but only at the one-loop level without the usual logarithmic enhancement factors. This is an attractive possibility that allows for the standard thermal leptogenesis while keeping the lepton-flavor violation at minimum [62].
the other hand, the Kähler potential term

$$\int d^4\theta \frac{1}{M_{Pl}} L H_u N$$  \tag{5}

is allowed. Normally, such a term is discarded because it is a total derivative within the global supersymmetric theory. However, the supersymmetry breaking effects appear for any dimensionful couplings in the theory, and this term is dimensionful due to the Planck-scale suppression. It can be represented by the Weyl compensator $\Phi = 1 + \theta^2 m^{3/2}$, which appears in the above term as

$$\int d^4\theta \Phi^* \frac{1}{M_{Pl}} L H_u N$$

$$= \int d^2\theta m^{3/2} M_{Pl} L H_u N + O(m^{3/2})$$  \tag{6}

The first term is extremely interesting: the neutrino Yukawa coupling is generated but is suppressed by $m^{3/2}/M_{Pl}$. This is different from the usual seesaw mechanism, giving Dirac neutrinos instead of Majorana neutrinos, yet their masses are naturally suppressed as $m^{3/2}/M_{Pl} \simeq 10$ meV. This is actually closer to the data of 9–50 meV than the standard GUT-based seesaw that predicts $m_o \simeq 1$ meV. Moreover, it is esthetically pleasing because we do not need to rely on a new energy scale, i.e. the GUT-scale or the seesaw scale, to “explain” the neutrino mass. It is simply one of the Planck-scale suppressed operators.

2.5. Consistent Framework

Recently, the successful electroweak symmetry breaking has been demonstrated within the framework of the anomaly mediation with the $D$-terms [59], which works particularly well with the recently proposed Minimal Supersymmetric Fat Higgs [60] or a variant of the Next-to-Minimal Supersymmetric Standard Model with extra vector-like quarks and leptons [61]. Therefore there are consistent models of anomaly mediation with no apparent phenomenological problems, no flavor or CP problems, no gravitino problem, and predicts naturally light Dirac neutrinos.

The superparticle spectrum of the anomaly mediation is quite different from many other frame-works (see Fig. 5), in particular the peculiar ratio among the gaugino masses due to the gauge beta functions. The Higgs sector is also likely to be richer than the standard MSSM with unusual mass spectra (see Fig. 6). Future experiments, which require at least the LHC and the ILC, but possibly also VLHC or CLIC, may well verify such unusual superparticle spectra.

2.6. Dirac Leptogenesis

Having presented a model of naturally light Dirac neutrinos, an obvious question arises: how do we understand the baryon asymmetry of the universe? The lepton number violation in Majorana neutrinos is the crucial ingredient in the leptogenesis [10].

Dirac leptogenesis overcomes this problem by the following simple observation [31]. Recall that the Dirac neutrinos have tiny Yukawa couplings, $m_\nu = Y_\nu v$, $Y \simeq m_{3/2}/M_{Pl} \simeq 10^{-11}$. If this is the only interaction of the right-handed neutrinos, thermalization is possible only by the process $NL \rightarrow HW$ etc, and they do not thermalize for $T \gtrsim g^2 Y^2 v M_{Pl} \sim 10 \text{ eV}$. (A similar but less dra-
matic point about the electron Yukawa coupling was made in [64].) At this low temperature, obviously both $H$ and $W$ cannot be produced and the thermalization is further delayed until $T_\nu \simeq m_\nu$ when neutrinos become non-relativistic. Therefore the number of left-handed and right-handed neutrinos are separately conserved practically up to now. We call them $L$ and $N$, respectively, and the total lepton number is $L + N$. The combination $L + N - B$ is strictly conserved.

Suppose the decay of a heavy particle produced an asymmetry $L_0 = -N_0 \neq 0$. The overall lepton number is conserved (see Fig. 7). $N_0$ is frozen down to $T_\nu$. On the other hand, the lepton asymmetry $L_0$ is partially converted to the baryon asymmetry via the standard model anomaly [65], [66]. Following [66], the chemical equilibrium due to the sphaleron leads to $B \simeq 0.35(B - L_0) = 0.35N_0 \neq 0$ and $L \simeq -0.65(B - L_0) = -0.65N_0$. After the electroweak phase transition $T \lesssim 250$ GeV, the anomaly is no longer effective and $B \neq 0$ is frozen. Finally at $T_\nu$, $L$ and $N$ equilibrate with the total lepton asymmetry $L + N = 0.35N_0$. In the end there is a baryon asymmetry $B = (L + N) \simeq 0.35N_0$.

The original paper [31] introduced new electroweak doublet scalar $\phi$ that has the same quantum numbers as the Higgs doublets and Yukawa couplings $\phi LN$ and $\phi^* LE$. Note that the model is not supersymmetric and hence the scalar field $\phi$ have Yukawa coupling with complex conjugation. If there are two sets of them, there is CP violation and their decays can create the asymmetry $L = -N \neq 0$. A supersymmetric generation [32] would require two separate chiral superfields $\phi$ and $\tilde{\phi}$, and a superpotential coupling $\phi LN + \phi^* LE + M_\phi \phi \tilde{\phi}$. This works with the anomaly-mediated supersymmetry breaking.

2.7. (Nearly) Verifiable Framework

Unlike the standard seesaw mechanism, the framework proposed here is nearly verifiable. (1) We need to find supersymmetry at the LHC, and measure its spectrum at the ILC. We can verify the mass spectrum of anomaly mediation with $D$-terms. (2) We may establish Dirac nature of neutrinos. For instance, if the long-baseline neutrino oscillation experiments establish the inverted hierarchy of the (light) neutrino spectrum (Fig. 8),
and if the neutrinoless double beta decay sets a limit that $|\langle m_{ee} \rangle| = |\sum_{i=1}^{3} U_{ei}^2 m_{\nu_i}| < 0.01$ eV, the Majorana neutrino hypothesis is excluded (see Fig. 9). Then the standard seesaw mechanism is safely excluded, while there are strong experimental indications for this framework.

3. sMajorana

Alternatives to the seesaw are not limited to Dirac neutrinos. Here I present a model where the light Majorana neutrinos are obtained yet the right-handed neutrinos are present at the electroweak scale, and hence offer the testability at collider experiments.

Let us come back to the question “why are neutrinos this light?” In the standard seesaw mechanism, the answer is that it is suppressed by the GUT-scale, $m_\nu \sim v^2/M_{\text{GUT}}$, where $v = 176$ GeV is the scale of the Higgs boson condensate. Once one takes supersymmetry seriously, this is not the only hierarchy we can use; the supersymmetry breaking scale is supposed be similar (but slightly higher) than the electroweak scale. Indeed, it is possible to write down a model where the neutrino mass is given by $m_\nu \sim m_{\text{SUSY}}^2/M_{\text{Pl}} \sim 1$ meV for $m_{\text{SUSY}} \sim 1$ TeV. In this discussion, I do not assume the anomaly-mediated supersymmetry breaking, but rather more conventional supergravity models.

In typical supergravity models, there is a field that breaks supersymmetry at an intermediate scale $m_I \simeq (m_{\text{SUSY}} M_{\text{Pl}})^{1/2}$. It is quite plausible that the field also has a supersymmetric expectation value of the comparable size, namely $\langle X \rangle \simeq m_I + \theta^2 m_I^2$. Then the following Lagrangian

$$\int d^2\theta \frac{X}{M_{\text{Pl}}} L H_u N + \int d^2\theta \frac{X^*}{M_{\text{Pl}}} N N$$

picks up the expectation value of $X$ and gives

$$\int d^2\theta \frac{m_{\text{SUSY}}}{M_{\text{Pl}}} L H_u N + m_{\text{SUSY}} ^* L H_u \tilde{N}$$

$$+ \int d^2\theta m_{\text{SUSY}} N N.$$  

Figure 8. Two possible mass spectra of neutrinos.

Figure 9. If the spectrum is inverted, there is a minimum size for the effective neutrino mass $|\langle m_{ee} \rangle|$ for the neutrinoless double-beta decay.
Therefore, the neutrino Yukawa coupling is given by
\[ Y_\nu \simeq \sqrt{m_{\text{SUSY}}/M_{\text{Pl}}} \simeq 10^{-7.5}, \]
while the right-handed neutrino has the mass of order TeV.

There is a little seesaw when the right-handed neutrinos are integrated out, giving the Majorana mass of light neutrinos
\[ m_\nu \simeq m_{\text{SUSY}}^2/M_{\text{Pl}} \simeq 1 \text{ meV}, \]
as advertised. The main difference from the standard seesaw is that the right-handed neutrinos are light, allowing for direct experimental tests. The Lagrangian presented above can be natural with a $U(1)_R$ symmetry, under which charges are assigned as $N(2/3)$, $X(4/3)$, $L(0)$, $H_u(0)$.

A very interesting term in the above Lagrangian is the trilinear scalar coupling
\[ m_{\text{SUSY}} \tilde{L}H_u \tilde{N}. \]
Once the Higgs boson acquires a VEV, it gives the left-right mixing mass-squared term of $O(m_{\text{SUSY}}^2)$, comparable to the left-left and right-right sneutrino mass-squared terms. Therefore, we expect the left-handed sneutrino $\tilde{\nu}$ and right-handed sneutrinos $\tilde{N}$ to mix with an $O(1)$ angle. This is quite unique to this framework. In particular, when sneutrinos are produced at collider experiments, we have a chance to see the mixture of the right-handed component, proving that there are right-handed sneutrinos at the electroweak scale. This would be a clear evidence that the standard seesaw is not at work.

The fact that the left-handed and right-handed sneutrinos mix substantially is also very interesting for cosmology. The sneutrino can be a viable Dark Matter candidate. For a normal left-handed sneutrino, the annihilation cross section is too large to leave enough abundance and/or the detection cross is too large and is already excluded by the direct detection experiments (see, e.g., [71]). The mixture of left- and right-handed sneutrinos evade both problems. The annihilation cross section is suppressed by $\sin^4 \theta$ where $\theta$ is the left-right mixing angle.

From the point of the direct detection experiments, there is another highly suppressed operator that turns out to be interesting:

\[ \int d^4 \theta \frac{XX^\ast X^\ast}{M_{\text{Pl}}^4} NN \equiv \frac{m_{\tilde{\nu}}^2}{M_{\text{Pl}}^2} \tilde{N} \tilde{N}. \]  

It violates the lepton number and mixes the right-handed sneutrino and the anti-right-handed sneutrino. The mixing between a scalar and its anti-particle is reminiscent of the neutral kaon and $B$-meson systems. It gives the mass splitting between two mass eigenstates, one CP-even and the other CP-odd, of the order of $\Delta m \simeq (m_{\text{SUSY}}^2/M_{\text{Pl}})^{1/2} \simeq 100 \text{ keV}$. This number is particularly interesting because it is roughly the kinetic energy of the dark matter particles in our galactic halo $\frac{1}{2} m v^2 \simeq \frac{1}{2} (100 \text{ GeV})(10^{-3})^2 = 50 \text{ keV}$.

It has been known that the lepton-number violation in the sneutrinos has an important consequence on the direct detection experiments because it will kill the diagonal coupling to the $Z$-boson. The two mass eigenstates, CP-even $\tilde{\nu}_+$ and CP-odd $\tilde{\nu}_-$, can couple only off-diagonally, $Z-\tilde{\nu}_+\tilde{\nu}_-$. This is a simple consequence of the Bose symmetry: two identical bosons cannot be in $P$-wave. In direct detection experiments, the dominant scattering process is the exchange of the virtual $Z$-boson between the sneutrino and
the nucleus. However, it is not an elastic scattering, but an *inelastic* process that transforms the sneutrino mass eigenstate $\tilde{\nu}_1$ to a heavier state $\tilde{\nu}_2$. Because the mass splitting is approximately the same as the kinetic energy, the dark matter scattering cross section is affected *kinematically* by the lepton-number violation. Only a part of the phase space $v^2 \geq \Delta m \frac{m_{\tilde{\nu}} + m_A}{m_A}$, where $m_A$ is the mass of the nucleus, allows for the inelastic scattering of the sneutrino kinematically.

This dark matter candidate can reconcile [75, 76] the claimed 6.3 $\sigma$ evidence for the dark matter detection by the DAMA experiment [73] and the negative search by the CDMS-II experiment [74]. The DAMA evidence is based on the annual modulation of the event rate that is interpreted as a consequence of the slight shifts in the phase space distribution of Dark Matter particles due to the motion of the Earth relative to that of the solar system inside the Milky Way galaxy. The kinematic selection of a part of the phase space due to the inelasticity enhances the annual modulation effect. Moreover, the heavier iodine nucleus (NaI in DAMA) has the larger phase space available than the lighter germanium (CDMS) and makes the signal larger in DAMA. The global fit to both data sets suggests a good fit and the mass difference of about 100 keV as expected [77].

The collider signature is also quite interesting. Because the sneutrino is the LSP, every superparticle decays eventually down to the sneutrino state. It can cause a very confusing situation in interpreting the signal [78]. The chargino decays into a charged lepton and missing energy, normally associated with the slepton signal. The slepton decays into two jets and missing energy, normally associated with the chargino signal. The signature at the LHC may be completely misinterpreted. Sorting it out is not easy even at the ILC, but it is possible in principle to choose the correct interpretation by measuring the spins of superparticles for each signal topology, their threshold behavior, their cross sections, decay angle distributions, and azimuthal correlation between decay planes [79].

Moreover, the measurement of the left-right mixing angle is possible in the heavier sneutrino production [80]. It allows also for the measure-

---

**Figure 11.** The coupling of the CP-odd and CP-even sneutrino mass eigenstates to the Z-boson is off-diagonal.

**Figure 12.** Preferred region of the parameter space for the inelastic Dark Matter by the DAMA experiment [73]. The horizontal axis $\delta$ is the mass splitting between the two mass eigenstates, while the vertical axis is the cross section on a nucleon assuming the spin-independent coherent matrix element.
Figure 13. Limit on the elastic spin-independent coherent scattering cross section of Dark Matter from CDMS-II, together with the preferred region from DAMA [74].

Figure 14. Unusual signatures of slepton and charginos that are interchanged from the conventional scenarios.

Figure 15. The azimuthal correlation between two decay planes from the chargino pair production in dilepton+missing topology. Together with the clear two-body kinematics in the charged lepton energy distribution, it establishes that it is a spin-1/2 particle, excluding the slepton interpretation of the signal [79].

4. Conclusions

Despite its attraction, the standard seesaw mechanism has many problems. The consistent...
anomaly mediation allows naturally light Dirac neutrinos at the correct order of magnitude for the neutrino mass, and solves the flavor, CP, and gravitino problems. The sMajorana model achieves a little seesaw with right-handed neutrinos below TeV, giving rise to direct collider tests and inelastic Dark Matter that reconciles DAMA and CDMS-II. It is clear that it is worthwhile pursuing alternatives to the seesaw with a keen attention to the testability.

Nonetheless the spirit of the seesaw lives: small neutrino mass is a window to the physics beyond the Standard Model.

This work was supported by the Institute for Advanced Study, funds for Natural Sciences, as well as in part by the DOE under the contract DE-AC03-76SF00098 and in part by the NSF grant PHY-0098840.

REFERENCES

17. H. Murayama, “Flavor in supersymmetry,” for Theoretical Advanced Study Institute in Elementary Particle Physics (TASI}

**Acknowledgments**

I thank the organizers of the seesaw25 workshop for the excellent organization and exciting workshop, and in particular to Prof. Kenzo Nakamura for his patience waiting for my manuscript.

http://hitoshi.berkeley.edu/TASI/


55. A. E. Nelson and N. T. Weiner,