Realistic Dirac Leptogenesis

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We present a model of leptogenesis that preserves lepton number. The model maintains the important feature of more traditional leptogenesis scenarios: the decaying particles that provide the CP violation necessary for baryogenesis also provide the explanation for the smallness of the neutrino Yukawa couplings. This model clearly demonstrates that, contrary to conventional wisdom, neutrinos need not be Majorana in nature in order to help explain the baryon asymmetry of the universe.

INTRODUCTION

One interface between particle physics and cosmology is the attempt to provide an explanation for the observed baryon asymmetry in the universe. Leptogenesis represents one of the most attractive possibilities for the generation of this asymmetry. The recent discovery of neutrino masses has further increased the credibility of this scenario. In its original incarnation, leptogenesis relies upon the decay of right-handed Majorana neutrinos to create lepton number, which is subsequently transformed into baryon number by the electroweak $B + L$ anomaly. This traditional scenario relies in an essential way on the breaking of lepton number by the Majorana right-handed neutrinos. The attractive feature of this model is that the right-handed neutrinos responsible for the generation of the lepton asymmetry are also responsible for the smallness of the observed neutrino masses through the see-saw mechanism.

Since the original model of (Majorana) leptogenesis, there have been two important observations. First, the provoking observation has been made that it is not necessary to break lepton number to have a theory of leptogenesis, and that leptogenesis could be accomplished in a theory with Dirac neutrinos. We will review this idea in the next section. A disadvantage of this idea, relative to the traditional models of leptogenesis, is that it possesses no relationship between the mechanisms responsible for the generation of the lepton asymmetry and the smallness of the neutrino masses. The second observation was that, in supersymmetric theories, it is possible to explain the smallness of the neutrino Yukawa couplings by relating their presence to supersymmetry breaking.

Combining these two ideas allows us to once again relate the generation of the lepton asymmetry to the smallness of neutrino masses.

This brings Dirac leptogenesis on to a footing equal to that of the traditional Majorana leptogenesis models. The only ingredient that this mechanism requires beyond the usual leptogenesis scenario is a $U(1)_N$ symmetry, which forbids the bare Yukawa couplings between the left and right-handed neutrinos.

REVIEW OF LEPTOGENESIS WITH DIRAC NEUTRINOS

Reference noted that, even in a theory that conserves lepton number, a CP violating decay of a heavy particle can result in a non-zero lepton number for left-handed particles, and an equal and opposite non-zero lepton number for right-handed particles. For most standard model species, Yukawa interactions between the left-handed and right-handed particles are sufficiently strong to cancel these two stores of lepton number rapidly. However, the interactions of a right-handed Dirac neutrino are exceedingly weak, and equilibrium between left-handed lepton number and right-handed lepton number will not be reached until temperatures fall well below the weak scale. By this time lepton number has already been converted to baryon number by sphalerons.

To see how this scenario works, imagine that a negative lepton number is stored in the left-handed neutrinos, while a positive lepton number of equal magnitude is stored in the right-handed neutrinos. Sphalerons act only on left-handed particles, violating $B + L$ while conserving $B - L$. This means part of the negative lepton number stored in left-handed neutrinos can be converted to a positive baryon number by the electroweak anomaly. The (now smaller in magnitude) negative lepton number stored in the left-handed neutrinos ultimately equilibrates with the positive lepton number stored in the right-handed neutrinos only after the temperature of the Universe drops below electronvolts. The processes responsible for equilibrating the right and left-handed neutrinos conserve both $B$ and $L$ separately. The ultimate result is a universe with a total positive lepton number and a total positive baryon number.

SMALL YUKAWA COUPLINGS

The basic program in this letter is to generate small Dirac Yukawa couplings by integrating out a heavy field following the methods of . The smallness of the Yukawa couplings will be explained by the large ratio be-
The right-handed neutrino (fermion) remains intact. In-
handed and right-handed sneutrinos equilibrate quickly
following superpotential:

\[ \langle \chi \rangle = 0 \text{ in the limit of global super-
}

Because \( \langle \chi \rangle \) does not have to be exactly at the
electroweak scale, it gives an additional freedom beyond
the traditional Majorana leptogenesis. We note that a very
similar superpotential was considered in [3], with the vev
of the \( \chi \) field replaced with a hard mass.

**LEPTON ASYMMETRY**

It remains to check whether this scenario can generate
a sufficient baryon asymmetry. CP violation will enter
the theory through the decay of the \( \phi \) and \( \bar{\phi} \) particles.
There are equal contributions from the decay of the scalar
and fermionic components. For simplicity, we will con-

TABLE I: The field content and quantum numbers of the
model.

| Field | \( U(1)_L \) | \( U(1)_N \) | \( SU(2)_L \) | \( U(1)_Y \) |
|-------|-------------|-------------|-------------|-------------|
| \( N \) | -1 | +1 | 1 | 0 |
| \( L \) | +1 | 0 | 2 | -\frac{1}{2} |
| \( H_u \) | 0 | 0 | 2 | \frac{1}{2} |
| \( \phi \) | +1 | -1 | 2 | \frac{1}{2} |
| \( \bar{\phi} \) | -1 | +1 | 2 | \frac{1}{2} |
| \( \chi \) | 0 | -1 | 1 | 0 |

In any case, it is clear that the Dirac neutrino Yukawa
couplings, \( y_\nu \), will be suppressed by the ratio of the weak
scale to the heavy masses:

\[ y_\nu \sim \frac{h_\lambda \langle \chi \rangle}{M^\phi}. \tag{3} \]

Now we proceed with the calculation of the asymmetry.
In the case where the magnitudes of the masses
\(|M_1|\) and \(|M_2|\) are well separated, the asymmetry
will be dominated by the decay of the lightest \( \phi \) - \( \bar{\phi} \) pair (we take
\(|M_1| < |M_2|\)) and can readily be calculated (following
the methods of [3]). We now define the quantities \( J \equiv
Im(h_\beta \bar{h}_\beta \lambda_{1a} \lambda_{2a} M_1 M_2) \) and \( \Delta M^2 \equiv |M_1|^2 - |M_2|^2 \).
In \( J \), the \( \alpha \) and \( \beta \) indices run over the genera-
tions of the \( L \) and \( N \) particles. For the decay asymmetries, we find:

\[ \epsilon_N \equiv \frac{\Gamma(\phi_1 \to N \chi_{\nu}) - \Gamma(\bar{\phi}_1 \to N H_u)}{\Gamma(\phi_1)} \]

\[ \frac{J}{4\pi \Delta M^2} \left( |\lambda_{1a}|^2 + |\lambda_{2a}|^2 \right) \equiv \varepsilon; \tag{5} \]

\[ \epsilon_L \equiv \frac{\Gamma(\phi_1 \to L \chi_{\nu}) - \Gamma(\bar{\phi}_1 \to L^c \chi^c)}{\Gamma(\phi_1)} \equiv -\varepsilon; \tag{6} \]
The one-loop diagrams contribute to the CP asymmetry. Asymmetry in FIG. 1: Diagrams giving the leading contribution to the CP asymmetry in $\phi$ and $\phi$ scalar decays. The absorptive part of the one-loop diagrams contributes to the CP asymmetry.

$$\epsilon_L = \frac{\Gamma(\bar{\phi}_1 \rightarrow L' \chi') - \Gamma(\bar{\phi}_1 \rightarrow L \chi)}{\Gamma(\phi_1)} = \epsilon;$$ (7)

$$\epsilon_N = \frac{\Gamma(\bar{\phi}_1 \rightarrow NH_0) - \Gamma(\bar{\phi}_1 \rightarrow N' H_0^*)}{\Gamma(\phi_1)} = -\epsilon. \quad (8)$$

Note that $\Gamma(\phi) = \Gamma(\bar{\phi})$ due to supersymmetry, because chiral superfields $\phi$ and $\bar{\phi}$ form a massive super-multiplet. Here we have used the same names for fermion and scalar fields in the same multiplet, and the $\alpha$ and $\beta$ indices labeling the generation of the final state particles are summed over. The above asymmetries in the decay amplitude give rise to a store of lepton number in the left-handed and right-handed (s)neutrinos. In the limit that the particles decay well out-of-equilibrium (the “drift and decay” limit), the asymmetry is given by [12]:

$$N \equiv \frac{n_N}{s} \sim \frac{\epsilon_N - \epsilon_N}{g_s n_\gamma} \sim \frac{-2\epsilon}{g_s} \quad (9)$$

$$L \equiv \frac{n_L}{s} \sim \frac{\epsilon_L - \epsilon_L}{g_s n_\gamma} \sim \frac{-2\epsilon}{g_s} \quad (10)$$

However, this limit is not necessarily applicable, as the condition for out-of-equilibrium decay, $\Gamma(\phi_1)/2H(M_1) \lesssim 1$, is only marginally satisfied. Therefore, one should solve the full system of Boltzmann equations numerically, including $2 \rightarrow 2$ scattering, to accurately determine the lepton asymmetry. However, for an existence proof that this mechanism will work, we will not need to resort to these numerics: we simply note that for the specific choices of $\lambda = h^T$ and $\langle \chi \rangle$ equal to the electroweak vev, our asymmetry (and neutrino mass matrices) will reduce to that of the standard supersymmetric leptogenesis scenario with Majorana neutrinos. It has been shown (for recent reviews see [13]), that the generation of a sufficient lepton asymmetry is possible in this case, with the mass of heavy neutrinos at the $10^{10}$ GeV scale. Indeed, it is possible that more complicated textures for $\lambda$ and $h$ might lead to a more efficient generation of a lepton asymmetry while remaining consistent with low-energy data on neutrino oscillations.

**COSMOLOGICAL AND ASTROPHYSICAL CONSTRAINTS**

Theories of supersymmetric leptogenesis have tension with the gravitino problem; the reheat temperature must be low enough to avoid cosmological difficulties associated with gravitino production. A typical constraint is $T_{RH} \lesssim 10^9\,10^{10}$ GeV for 1–2 TeV gravitino [13]. On the other hand, the reheat temperature must be high enough to produce the particles (in our case the $\phi$ and $\bar{\phi}$) that need to be heavy in order to decay out of equilibrium. However, as we have shown above, our scenario can reproduce a baryon asymmetry equal to that of the traditional leptogenesis scenario, which has been shown to be compatible with gravitino constraints [13]. There are a host of other ideas to help with this tension. For example, theories of anomaly mediation [14], have gravitino masses that are heavier than the usual case by a loop factor, of order 100 TeV. Furthermore, there has been recent work suggesting that it may be possible to significantly increase the mass of the gravitino in theories with weak scale supersymmetry, thereby obviating the gravitino problem [13].

Yet another possibility involves using coherent oscillations of the scalar fields carrying lepton number [12, 17]. In our case the $\phi = \phi$ flat direction could be used, for example, with the O’Raifeartaigh model discussed earlier with $\kappa \sim 1$, $\langle \chi \rangle \sim 10$ TeV. We make the assumption that $N$ and $L$ remain pinned to the origin. If we stick to the simplifying ansatz $\lambda = h^T$, we can scale $M^8$ proportional to $\langle \chi \rangle$ so as to reproduce the observed neutrino masses with the same Yukawa couplings as the traditional case. This means that the CP asymmetry remains the same as well. Working within the model of [17] (replacing $N$ with the $\phi = \phi$ flat direction), in order to have the CP asymmetry large enough, we require $M^8 \gtrsim 10^8$ GeV. This can well be consistent with the gravitino mass of $\sim 1$ TeV. In addition, the possibility $\lambda \neq h^T$ gives even more freedom.

It would be interesting to study the gravitino problem with both $\langle \chi \rangle$ and $\langle F_\chi \rangle$ (and hence the gravitino mass) as free parameters, such as in models of gauge-mediated supersymmetry breaking. Smaller $\langle F_\chi \rangle$ gives a lighter
gravitino, and the constraint on the reheat temperature is more severe \cite{21}. However, smaller \( \langle F \chi \rangle \) allows smaller \( \langle \chi \rangle \) while preventing the appearance of a negative eigenvalue in the neutrino mass-squared matrix. This, in turn, would allow for lighter \( \phi \), which helps with the gravitino problem. Therefore, we expect Dirac leptogenesis to accommodate models with lower \( \langle F \chi \rangle \) more easily than traditional leptogenesis models.

There might be a worry that the right-handed neutrinos could potentially represent a dangerous number of additional light species at the time of Big-Bang Nucleosynthesis (BBN). The constraint is \( \Delta N_\nu \lesssim 0.3 \) \cite{19}. However, by the time of BBN, the contribution of right-handed neutrinos is suppressed by the entropy factor: \( \Delta N_\nu = 3(T_{\nu R}/T_{\text{bath}})^4 = 3|g_\ast (1\text{MeV})/g_\ast (\text{MSSM} + \nu)|^{4/3} = 0.02 \) and is safe.

When the \( U(1)_N \) symmetry is broken by the \( \chi \) vev or \( F \) vev, a Nambu-Goldstone boson will be produced. Generally, stringent astrophysical constraints on such particles (e.g., Majorons, familons) are derived from looking at supernovae. The usual constraints assume couplings between the SM fields and the Nambu-Goldstone bosons. In contrast, in this case the right handed neutrino is the only light field charged under the \( U(1)_N \). Consequently, the couplings of the Nambu-Goldstone bosons to the matter in the supernova will be exceedingly weak. Nambu-Goldstone boson production processes will be suppressed by factors of \( m_\nu/T \) relative to the usual case. Since even the usual case (see, for example, \cite{20}), can be made acceptable, there is clearly no problem here.

**CONCLUSION**

We have presented a realistic model of supersymmetric leptogenesis using Dirac neutrinos. The smallness of the 
\( N_{\text{Yukawas}} \) is related to the presence of heavy fields whose decay provides the seed for the baryon number of our universe. The only ingredient used in this scenario above and beyond the usual leptogenesis scenario is the imposition of a \( U(1)_N \) symmetry. It would be interesting to search for a fundamental origin for this symmetry. Because of the simplicity of this model, we believe that leptogenesis with Dirac neutrinos should be placed on an equal footing with the usual Majorana leptogenesis scenarios.

This model clearly displays that neutrinos need not be Majorana in order for them to play a major role in the generation of the baryon asymmetry. In this scenario, leptogenesis will not give rise to any signal in neutrino-less double beta decay experiments.

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