Neutrino Mass, the Strong CP Problem, and Baryon Number Violation

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Canonical Seesaw Origin of Neutrino Mass

$$\mathcal{L}_N = f_{ij}(\nu_i \phi^0 - l_i \phi^+) N_j^c - m_{N_i} N_i^c N_i^c / 2 + H.c.$$
$$\Rightarrow (\mathcal{M}_\nu)_{ij} = -f_{ik} f_{jk} \langle \phi^0 \rangle^2 / m_{N_k}.$$

Without m_N, ν has $L = +1$ and N^c has $L = -1$. With m_N, $L \to (-)^L$. Below the scale of m_N, all particle interactions conserve additive L except for rare processes involving the effective exchange of N^c such as neutrinoless double beta decay. This allows a lepton asymmetry to be established from the decay of N^c.

Axionic Solutions of the Strong CP Problem

The strong CP violating parameter

$\overline{\theta} = \theta_{QCD} - \sum_q Arg\ m_q - 3 Arg\ m_{\tilde{g}}$

is relaxed to zero if there is a dynamical phase attached to the ordinary quarks (DFSZ) or to unknown singlet heavy quarks (KSVZ) or to the gluinos (DM).

This is accomplished by the spontaneous breaking of $U(1)_{PQ}$, resulting in a singlet (or mostly singlet) axion at a very high scale: $10^9 < f_a < 10^{12}$ GeV, to be consistent with constraints from astrophysics and cosmology.

Supersymmetric Realization of $m_N \sim f_a$

superfield	$U(1)_{PQ}$	$(-)^L$
$Q = (u, d), u^c, d^c$	1/2	$+$
$L = (\nu, e), e^c, N^c$	1/2	$-$
$\Phi_1 = (\phi_1^0, \phi_1^-), \Phi_2 = (\phi_2^+, \phi_2^0)$	–1	$+$
S_2, S_1, S_0	2, –1, –2	$+$

$$W = m_0 S_0 S_2 + \lambda_1 S_1 S_1 S_2 + \lambda_2 S_1 N^c N^c + f_1 S_2 \Phi_1 \Phi_2 + f_d \Phi_1 Q d^c + f_u \Phi_2 Q u^c + f_e \Phi_1 L e^c + f_N \Phi_2 L N^c.$$

Two scales m_0 and M_{SUSY} are available. The usual μ term of the MSSM is replaced by $f_1\langle S_2\rangle$ and $m_N = 2\lambda_2\langle S_1\rangle$. This means that $\langle S_2\rangle << \langle S_1\rangle$ is required. Also, supersymmetry must remain exact after the breaking of $U(1)_{PQ}$ at f_a.

$V(S_{2,1,0}) = m_0^2|S_2|^2 + 4\lambda_1^2|S_1|^2|S_2|^2 + |m_0 S_0 + \lambda_1 S_1^2|^2$

$V = 0$ (to preserve supersymmetry) $\Rightarrow$

(A) $u_0 = u_1 = u_2 = 0$, or (B) $u_2 = 0,\ m_0 u_0 + \lambda_1 u_1^2 = 0$.

Choose (B) and shift $S_{2,1,0}$ by $u_{2,1,0}$, then

$$W' = \frac{m_0}{u_1}(u_1 S_0 - 2u_0 S_1)S_2 + \lambda_1 S_1 S_1 S_2.$$

Hence $\chi = (u_1 S_1 + 2u_0 S_0)/\sqrt{u_1^2 + 4u_0^2}$ is a massless superfield, which comes from the supersymmetric vacuum being invariant under both a phase rotation and a scale transformation, i.e. a flat direction.

Add $V_{soft} = \mu_0^2|S_0|^2 + \mu_1^2|S_1|^2 + \mu_2^2|S_2|^2$
$+ [\mu_{02} m_0 S_0 S_2 + \mu_{12} S_1^2 S_2 + H.c.]$, then

$$(m_0^2 + \mu_2^2 + 4\lambda_1^2 u_1^2) u_2 + \mu_{02} m_0 u_0 + \mu_{12} u_1^2 = 0,$$
$$2\lambda_1 (m_0 u_0 + \lambda_1 u_1^2) + \mu_1^2 + 2\mu_{12} u_2 + 4\lambda_1^2 u_2^2 = 0,$$
$$m_0 (m_0 u_0 + \lambda_1 u_1^2) + \mu_0^2 u_0 + \mu_{02} m_0 u_2 = 0.$$

$\Rightarrow u_2 \sim M_{SUSY}$, $u_{0,1} \sim m_0$ with $m_0 u_0 + \lambda_1 u_1^2 \sim M_{SUSY}^2$.

axion $a = (u_1\theta_1 + 2u_0\theta_0 - 2u_2\theta_2)/\sqrt{u_1^2 + 4u_0^2 + 4u_2^2}$.
axino $\tilde{a}$ has mass $6\lambda_1 u_2 u_1^2/(u_1^2 + 4u_0^2 + 4u_2^2)$.
saxion has mass $\sim M_{SUSY}$.
The μ term of the MSSM is replaced by $f_1 u_2 \Phi_1 \Phi_2$.
The μB term in the scalar sector is given by
$f_1[A_2 u_2 + (m_0 u_0 + \lambda_1 u_1^2)] \sim M_{SUSY}^2$.
Electroweak symmetry breaking is thus predicted to be $\sim M_{SUSY}$ in this scenario. $\langle \phi_{1,2}^0 \rangle = v_{1,2}$ means that the axion picks up a small component

$$\frac{2v_1 v_2}{v_1^2 + v_2^2}(v_1\varphi_2 + v_2\varphi_1).$$

Hence the axionic coupling to quarks is given by

$$\frac{\partial_\mu a}{2V}\left(\frac{2v_1v_2}{v_1^2+v_2^2}\right)\left[\frac{v_1}{v_2}\bar{u}\gamma^\mu\gamma_5 u+\frac{v_2}{v_1}\bar{d}\gamma^\mu\gamma_5 d\right]$$

$$=V^{-1}(\partial_\mu a)[\sin^2\beta\bar{u}\gamma^\mu\gamma_5 u+\cos^2\beta\bar{d}\gamma^\mu\gamma_5 d],$$

where $V=[u_1^2+4u_0^2+4u_2^2+4v_1^2v_2^2/(v_1^2+v_2^2)]^{1/2}$ and $\tan\beta=v_1/v_2$ as in the DFSZ model.

Axino mixes with neutralinos and saxion with Higgs scalars, but only by M_{SUSY}/f_a. Since R parity remains exact, dark matter = the lightest neutralino (axino) + axion.

Implementation of $B \to (-)^{3B}$

Suppose the analog of N^c exists for baryon number, i.e. Σ with $B = 1$, as well as the effective interaction $u_i^c d_j^c d_k^c \Sigma$. Assuming that Σ is allowed a large Majorana mass m_Σ, then $B \to (-)^{3B}$ as desired.

To implement this in a renormalizable theory, the simplest way is to introduce singlet scalar quark fields $\tilde{h}, \tilde{h}^c$ with charges $\mp 1/3$ and $B = \mp 2/3$, so that $ud\tilde{h}$, $u^c d^c \tilde{h}^c$, and $d^c \tilde{h} \Sigma$ are allowed. Deuteron decay and neutron-antineutron oscillations are now possible, but the proton is stable because $(-)^{3B}$ is conserved.

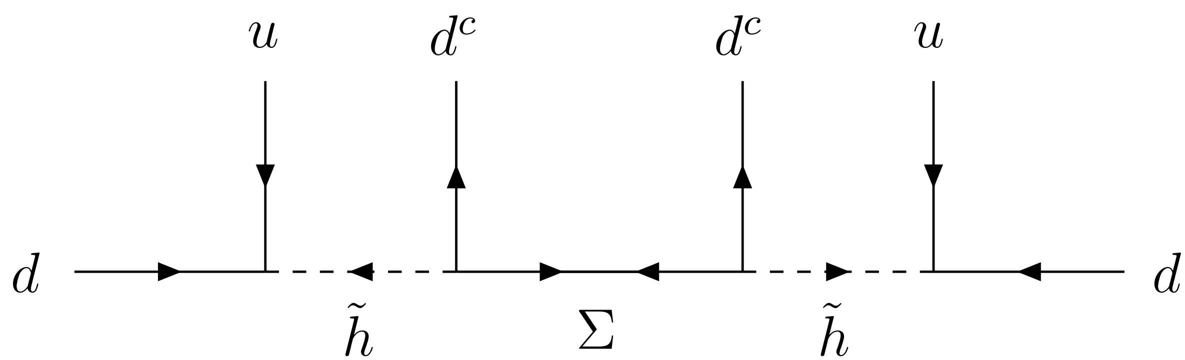

Figure 1: Diagram for deuteron decay and $n - \bar{n}$ oscillation.

The same mechanism may also be responsible for baryogenesis. The decay of the lightest Σ into udd or $u^c d^c d^c$ generates a B asymmetry, and below the m_Σ scale, additive B is conserved. This B asymmetry is then converted into a $B-L$ asymmetry through the intervention of the sphalerons during the electroweak phase transition. If $\tilde{h}$ or $\tilde{h}^c$ is kinematically accessible at the LHC, it will be copiously produced and decay into two quark jets, but in this scenario, the mass scales of $\tilde{h}$, $\tilde{h}^c$, and Σ are not separately constrained. There is no guarantee that $\tilde{h}$ or $\tilde{h}^c$ is of order TeV.

Common Origin of $(-)^L$, $(-)^{3B}$, and Strong CP Conservation

Combining $L \to (-)^L$, $B \to (-)^{3B}$ and $U(1)_{PQ}$, a supersymmetric model may be constructed.

superfield	$(-)^L$	$(-)^{3B}$	$U(1)_{PQ}$
Q, u^c, d^c, Σ	$+$	$-$	1/2
L, e^c, N^c	$-$	$+$	1/2
Φ_1, Φ_2	$+$	$+$	–1
h, h^c	$+$	$+$	–1
S_2, S_1, S_0	$+$	$+$	2,–1,–2

There are again only two mass scales: m_0 and M_{SUSY}, with $m_N \sim m_\Sigma \sim m_0$ and $m_h \sim M_{SUSY}$. In the early Universe, N^c (Σ) generates a L (B) asymmetry. Below $m_N \sim m_\Sigma$, both additive L and additive B are good. Sphalerons then convert both asymmetries into a $B - L$ asymmetry. [The $L\Phi_2 N^c$ couplings are constrained by neutrino mass, but the $d^c h \Sigma$ couplings are free.]

Gauge coupling unification is easily restored by the addition of Φ_3, Φ_4, which couple for example only to leptons whereas Φ_1, Φ_2 couple only to quarks. This would predict a much richer Higgs sector at the LHC.

- Strong CP problem is solved with a DFSZ axion in supersymmetry, with $\mu \sim M_{SUSY}$ and $\mu B \sim M_{SUSY}^2$.

- Seesaw neutrino mass is obtained with $m_N \sim f_a$.

- R parity is conserved $\Rightarrow$ neutralino (axino) could be dark matter as well as the axion.

- $B \to (-)^{3B}$ with Σ, h, h^c: $m_\Sigma \sim f_a$, $m_h \sim M_{SUSY}$.

- Separate L and B asymmetries $\to$ $B - L$ asymmetry.

- New particles OK with gauge coupling unification.