L and B Beyond the SM

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Introduction

In the minimal Standard Model (SM), it is well-known that lepton number (L) and baryon number (B) are automatic symmetries. Once new particles are added, their L and B assignments are not automatic, but dictated by how they interact with the SM particles.

This is especially true of a neutral fermion singlet. See the Brief Review: E. Ma, Mod. Phys. Lett. A32, 1730007 (2017). In this talk, I will touch upon some recent new ideas in extending L and B to accommodate the existence of dark matter (DM).

Early Thoughts on L

1979: Seesaw Neutrino Mass.

Add ν_R to SM and allow all possible new terms under $SU(3)_C \times SU(2)_L \times U(1)_Y$ with one Higgs doublet, i.e. $\bar{\nu}_R(\nu_L \phi^0 - l_L \phi^+)$ and $m_R \nu_R \nu_R$.

Usual interpretation: L is broken explicitly (but softly) by m_R. Residual symmetry is L parity $= (-1)^L$.

1981: Singlet Majoron Model.

Add ν_R and impose global L. Use $L = -2$ scalar singlet σ for the Yukawa term $\sigma \nu_R \nu_R$ and $\langle \sigma \rangle \neq 0$ to obtain m_R as well as a massless Goldstone boson, the singlet majoron.

1987: Shin, PRL 59, 2515.

Add color triplet fermion $Q_L \sim 1$ and $Q_R \sim -1$ under global L so that it is now anomalous and the term $\sigma \bar{Q}_R Q_L$ makes the singlet majoron into a QCD axion. This simple idea connects the neutrino seesaw scale to the axion scale, i.e $U(1)_L = U(1)_{PQ}$.

It is easily extended to SUSY: Ma(2001).

More recently, it has also been applied to radiative neutrino masses: Ma/Restrepo/Zapata(2018) and Ma/Ohata/Tsumura(2017).

More on this later together with the inclusion of B.

L Parity to Dark Parity

1985: Silveira/Zee, PLB 161, 136.

Add real scalar singlet s, odd under a new Z_2 with all SM particles even. Even if there is ν_R, the $s\nu_R\nu_R$ term is forbidden. Hence s is a possible DM candidate. For a recent comprehensive review, see GAMBIT, EPJC 77, 568 (2017).

2015: Ma, PRL 115, 011801.

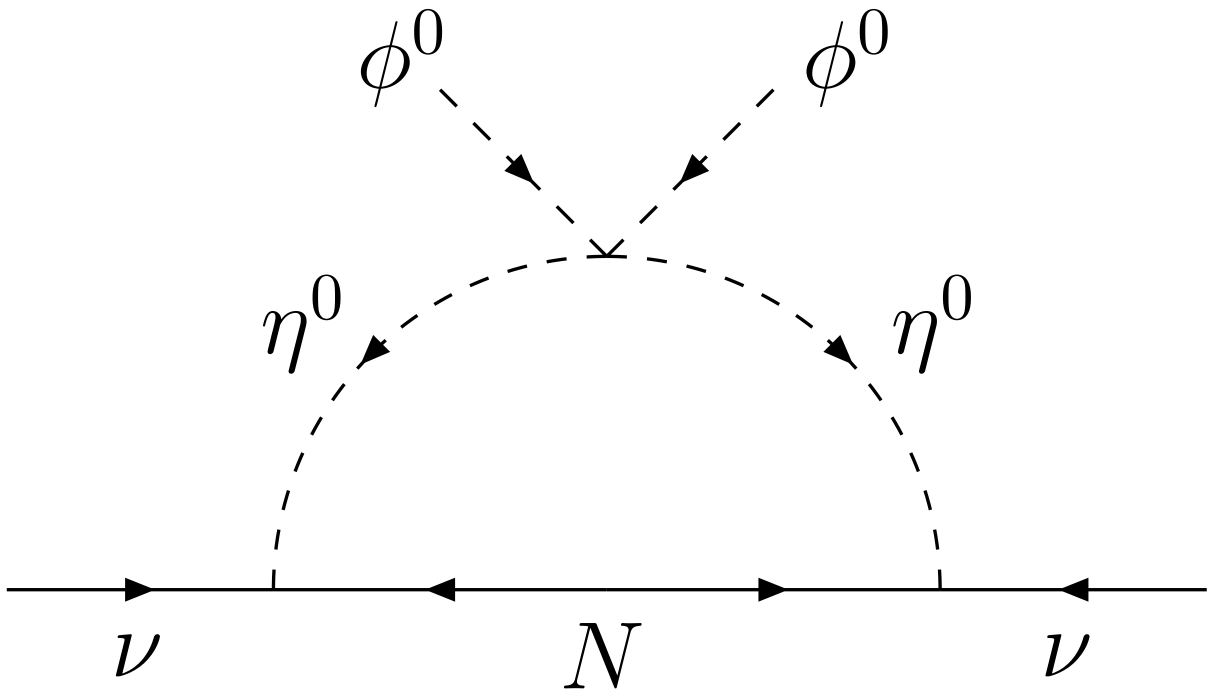
The Z_2 of the above model (and many other DM models) is derivable from L parity. To forbid $s\nu_R\nu_R$, s must have odd L parity. Dark parity is thus simply $(-1)^{L+2j}$.

2006: Scotogenic Neutrino Mass.

Add neutral Majorana singlet fermion N and scalar doublet (η^+, η^0), odd under Z_2. Radiative neutrino mass is thus generated from the allowed $m_N N N$, $(\nu\eta^0 - l\eta^+)N$, and $(\Phi^\dagger\eta)^2$ terms.

Again Z_2 is not necessary because we can simply assign (even,odd) L parity to (N, η).

This also works for the three-loop Krauss/Nasri/Trodden(2003), Aoki/Kanemura/Seto(2009), and Gustafsson/No/Rivera(2013) models.


ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

Z$_N$ L and Dirac Neutrino Mass

Lepton number is usually thought of as being an integer L or a parity $(-1)^L$. In the latter case, neutrinos are Majorana, which is the default option. In the former case, they are Dirac, and in the persisting nonobservation of neutrinoless double beta decay, there is a theoretical resurgence of interest in them.

What is new in the last few years is the realization that lepton number may be based on Z_N. There are already explicit examples of Z_3 and Z_4 models.

2013: Ma/Picek/Radovcic, PLB 726, 744.

Gauge U(1) breaks to global U(1) if $\sigma \sim 3$ with $\langle\sigma\rangle \neq 0$.

2013: Heeck/Rodejohann, EPL 103, 32001.

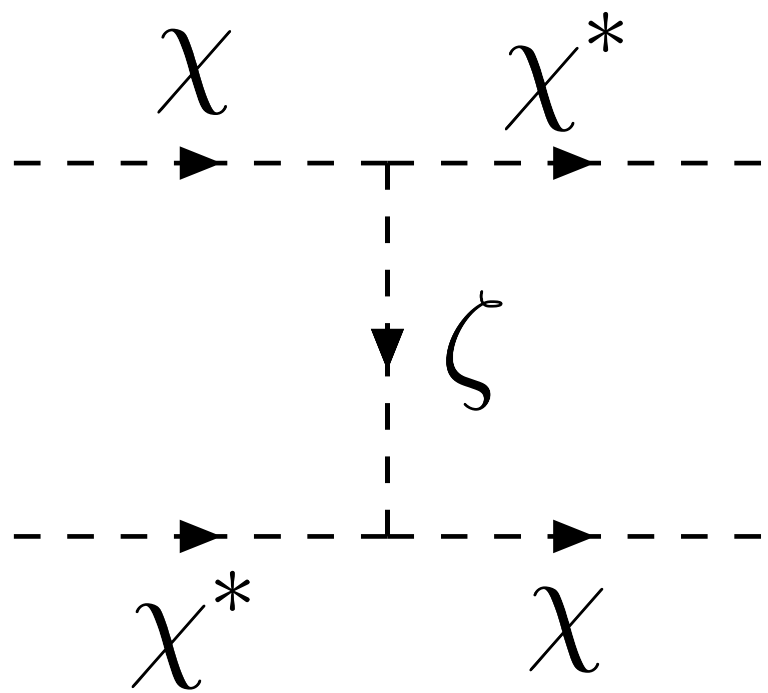
Gauge $B-L$ breaks to Z_4 with $\sigma \sim 4$ and $\zeta \sim 2$
$\Rightarrow 0\nu 4\beta$ decay.

2015: Ma/Pollard/Srivastava/Zakeri, PLB 750, 135.

Gauge $B-L$ breaks to Z_3 with $\sigma \sim 3, 6$ and $\chi \sim 2$
$\Rightarrow \chi \to \bar\nu\bar\nu$ decay with a very long lifetime.

2018: Ma, arXiv:1805.03295.

Under L, $\chi \sim 1$, $\zeta \sim 2$, with $\mu_{12}\zeta^*\chi^2$ and $\lambda_{12}(\chi^*\chi)(\zeta^*\zeta)$.


χ
χ^*
ζ
χ^*
χ

$$\sigma_{el}(\chi\chi^* \to \chi^*\chi) = \frac{\mu_{12}^4}{4\pi m_\chi^2 m_\zeta^4}.$$

$$\sigma_{ann}(\chi\chi^* \to \zeta\zeta^*) = \frac{1}{32\pi m_\chi^2}\left(\lambda_{12} + \frac{2\mu_{12}^2}{m_\chi^2}\right)^2.$$

Example: $m_\chi = 150$ GeV, $\lambda_{12} + 2\mu_{12}^2/m_\chi^2 = 0.0923$, then $\sigma_{ann}v_{rel} = 4.4 \times 10^{-26}\ cm^3/s$ (relic abundance). $m_\zeta/\mu_{12} = 0.0015$ yields $\sigma_{el}/m_\chi \simeq 1\ cm^2/g$ (cusp-core discrepancy). $\lambda_{12} > 0$ implies $\mu_{12} < 32.2$ GeV and $m_\zeta < 48.3$ MeV. $\zeta \to \nu_R\nu_R$ does not disturb the CMB.

B Beyond the SM

1988: Ma, PRL 60, 1363.

$E_6 \to SU(3)_C \times SU(2)_L \times SU(3)_R$:

$$
\begin{aligned}
q &\sim (3,3^*,1) \sim \begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix}, \\
\lambda &\sim (1,3,3^*) \sim \begin{pmatrix} E_1^0 & E^+ & \nu \\ E^- & E_2^0 & e \\ N^c & e^c & S \end{pmatrix} \\
q^c &\sim (3^*,1,3) \sim \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix}.
\end{aligned}
$$

In addition to all the necessary mass terms, suppose only 3 of the other 6 possible Yukawa terms are singled out by a discrete symmetry, i.e. $d^c N^c h$, QQh, $u^c d^c h^c$. Then h, h^c are diquarks with baryon number $B = \mp 2/3$ and N^c has $B = 1$. This is the first time that such a possibility was discussed, i.e. that the singlet right-handed neutrino is a baryon in disguise.

If the Majorana mass term $N^c N^c$ exists, then B is violated by 2 units, implying neutron-antineutron oscillation. Note that the proton is stable because it cannot decay into N^c kinematically.

2018: Ma/Tsumura, arXiv:1805.05056.

Combine $U(1)_L = U(1)_{PQ}$ with h as diquarks.

Instead of one scalar field, use two $S_{1,2}$ with $L = -1, -2$ with Yukawa couplings $S_1^* \bar{h}_L h_R$ and $S_2 N_R N_R$ as well as the cubic scalar term $S_2^* S_1^2$.

The L assignments of h_L and h_R are not yet completely fixed at this point, only that they must differ by one unit.

The scalar color triplet $\zeta \sim (3, 1, -1/3)$ is added with the Yukawa terms $\zeta u_L d_L$, $\zeta u_R d_R$, and $\zeta^* N_R h_R$. Hence ζ has $B = -2/3$ and $L = 0$ whereas $h_{L,R}$ has $B = -2/3$ and $L = 0, -1$.

Finally, the scalar singlet σ is added with the Yukawa term $\sigma^* \bar{h}_L d_R$, i.e. σ has $B = 1$ and $L = 0$.

Now $\langle S_{1,2} \rangle \neq 0$ break $U(1)_L = U(1)_{PQ}$ spontaneously, with the resulting majoron becoming the QCD axion. At the same time, $\langle \sigma \rangle \neq 0$ would generate a massless Goldstone with derivative couplings to baryons, which may be called the "sakharon", after Andrei Sakharov. In this model, the soft term σ^2 is added which breaks B by two units, so that only the residual baryon parity $(-1)^{3B}$ is conserved. The would-be massless Goldstone, i.e. $\sqrt{2} Im(\sigma)$ becomes a massive pseudo-sakharon S.

As the QCD axion has a very long lifetime, so does S. Both are components of dark matter.

Since $\langle\sigma\rangle \neq 0$, baryon parity is also broken, hence S couples to $\bar{d}\gamma_5 d$ through $d_L - h_L$ mixing which is strongly suppressed.

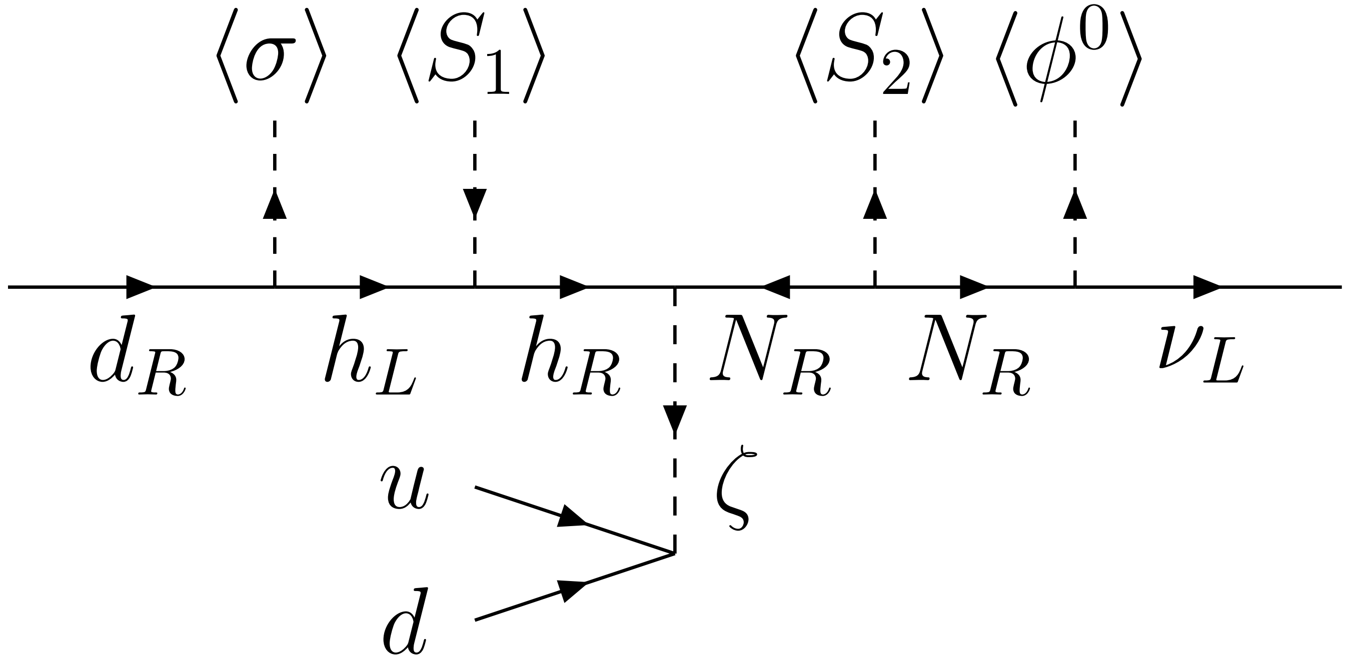
$$\Gamma(S \to d\bar{d}) \simeq \frac{m_S}{16\pi}(y_\sigma^d)^4 \left(\frac{m_d v_\sigma}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_d^2}{m_S^2}}.$$

Note that S does not mix with the SM Higgs boson because of automatic CP conservation in the scalar sector.

Proton decay is also possible through ζ, N, and h. The dominant operator is dim-7 (instead of the usual dim-6) and conserves $B+L$ (instead of $B-L$), i.e.

$$\mathcal{L}_7 = \frac{y_\zeta (y_\sigma v_\sigma) y_\nu}{m_\zeta^2 m_N m_h} (\bar{\nu}_L \bar{\phi}^0 d_R)(y_L u_L d_L + y_R u_R d_R).$$

Hence the dominant decay is $p \to \pi^+ \nu$ and not the usual $p \to \pi^0 e^+$. The conceptual difference of this scenario from most is that DM comes from broken B and L symmetries, but the resulting pseudo-sakharon and QCD axion decay very slowly and so does the proton.


$\langle\sigma\rangle$
$\langle S_1\rangle$
$\langle S_2\rangle$
$\langle\phi^0\rangle$
d_R
h_L
h_R
N_R
N_R
ν_L
u
ζ
d

2018: Ma/Sarkar/Tsumura, in progress.

Instead of $U(1)_L = U(1)_{PQ}$, it is also possible to have $U(1)_B = U(1)_{PQ}$. To do this, let $h_{L,R}$ and $\zeta_{L,R}$ each have $B = 1/3, -2/3$, i.e. ζ_R couples to $u_L d_L$ and $u_R d_R$ whereas h_R couples to $N_R \zeta^*$ (so h_R has odd lepton parity). [The usual seesaw neutrino mass is assumed with the allowed $m_N N_R N_R$ term.] Add a real scalar singlet s with odd lepton parity, then $s \bar{h}_L d_R$ means that h_L has $B = 1/3$, whereas $\sigma \bar{h}_L h_R$ and $\sigma \zeta_L^* \zeta_R$ require σ to have $B = 1$. Now s is long-lived DM, as is the QCD axion. Proton is still stable because lepton parity is conserved.

Concluding Remarks

The L and B of any new particle beyond the SM is not automatically fixed. It depends on context.

Interesting examples are already known for 30 years or more. Because of the need to understand dark matter, new particles were postulated in many models, without realizing this important connection.

New insights have emerged in recent years, including Z_N lepton number for Dirac neutrinos and (self-interacting) dark matter, as well as $U(1)_L = U(1)_{PQ}$, $U(1)_B = U(1)_{PQ}$, and a possible pseudo-sakharon.