Predictions of Additional Baryons and Mesons

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Abstract

We discuss the predictions of the bilepton model which is an extension of the standard model in which the group $SU(2) \times U(1)$ is changed to $SU(3) \times U(1)$ and the fermion families are treated non-sequentially with the third assigned differently from the first two. Cancellation of triangle anomalies and asymptotic freedom require three families. The predicted new physics includes bileptons and three heavy quarks $D$, $S$ and $T$. QCD will bind the heavy quarks to light quarks and to each other to form baryons and mesons which, unlike bileptons, are beyond the reach of the LHC but accessible in a hypothetical 100 TeV proton-proton collider.

Keywords: Triangle anomaly cancellation; three families; TeV quarks; additional baryons; additional mesons.

1 Introduction

In this talk we shall discuss what now seems likely to be the first new particle beyond the standard model and which is now being actively searched for at the LHC. The bilepton model, a better name than the 331-Model, was invented as an example of what then was expected to be a new class of models which require the existence three families. That invention was in 1992 [1] but it required a couple more years to realise that the expected new class of models has only one member.
We remain optimistic that LHC can find a discovery signal for the bilepton gauge boson in the remainder of 2022. What we can say generally is that to invent a model which is beyond the standard model, one generally aims to both (i) address and solve a question unanswered within the standard model, and to (ii) provide explicit predictions which are testable. The bilepton model beautifully fulfils both of these criteria.

Although not a sub-theory, the model originated from studying an interesting $SU(15)$ model in which the 224 gauge bosons couple to all possible pairs of the 15 states

$$\begin{align*}
(u, d)_{\alpha}; (\bar{u})_{\alpha}; (\bar{d})_{\alpha}; (\nu_e, e, \bar{e}).
\end{align*}$$

Every gauge boson therefore has a well-defined B and L so there can be no proton decay by tree-level gauge boson exchange.

In the $SU(15)$ model there is one unaesthetic feature that anomalies are cancelled by adding mirror fermions as in $15 + \bar{15}$. But persisting further, we considered the subgroups in $SU(15) \rightarrow SU(12) \times SU(3)_l$, especially the $SU(3)_l$ which contains an antitriplet $(e^+, \nu_e, e^-)$ where the $|L| = |Q| = 2$ bilepton can first be seen, coupling electron to positron.

The question then was: can a chiral model contain bileptons? After hundreds of trials and errors we found only one solution of the anomaly cancellation equations. This required non-sequential families where the third is assigned differently from the first two and explains why there must be three families. This is the bilepton model. It provides an answer to Rabi’s famous question when the muon was discovered in 1936: "Who ordered that?"

The non-sequentiality of families offers one explanation for the failure of the $SU(5)$ model studied first in 1974 then in hundreds of other papers. $SU(5)$ assumed sequentiality of families of the form $3(10 + 5)$.

In 1977 Weinberg and in 1984 Glashow both considered upgrading the electroweak $SU(2)$ of the standard model to $SU(3)$ but overlooked the assignments which explain three families.

2 Bilepton model

The gauge group is:

$$SU(3)_C \times SU(2)_L \times U(1)_X$$

(2)
The simplest choice for the electric charge is

\[ Q = \frac{1}{2} \lambda^3_L + \left( \frac{\sqrt{3}}{2} \right) \lambda^8_L + X \left( \frac{\sqrt{3}}{\sqrt{2}} \right) \lambda^9 \] (3)

where

\[ Tr(\lambda^a_L \lambda^b_L) = 2 \delta^{ab} \] (4)

and

\[ \lambda^9 \equiv \left( \frac{\sqrt{2}}{\sqrt{3}} \right) diag(1, 1, 1) \] (5)

Thus a triplet has charges \((X + 1, X, X - 1)\).

Leptons are treated democratically in each of the three families. They are colour singlets in antitriplets of \(SU(3)_L\) : 

\[
\begin{align*}
(e^+, \nu_e, e^-)_L \\
(\mu^+, \nu_\mu, \mu^-)_L \\
(\tau^+, \nu_\tau, \tau^-)_L
\end{align*}
\]

All have \(X = 0\).

Quarks in the first family are assigned to a left-handed triplet plus three singlets of \(SU(3)_L\).

\[
(u^\alpha, d^\alpha, D^\alpha)_L \ (\bar{u}_\alpha)_L, (\bar{d}_\alpha)_L, (\bar{D}_\alpha)_L
\]

Similarly for the second family

\[
(e^\alpha, s^\alpha, S^\alpha)_L \ (\bar{e}_\alpha)_L, (\bar{s}_\alpha)_L, (\bar{S}_\alpha)_L
\]

The \(X\) values are for the triplets are \(X = -1/3\) and for the singlets \(X = -2/3, +1/3, +4/3\) respectively. The electric charge of the new quarks \(D, S\) is \(-4/3\).

The quarks of the third family are treated differently. They are assigned to a left-handed antitriplet and three singlets under \(SU(3)_L\)

\[
(b^\alpha, t^\alpha, T^\alpha)_L \ (\bar{b}_\alpha)_L, (\bar{t}_\alpha)_L, (\bar{T}_\alpha)_L
\]

The antitriplet has \(X = +2/3\) and the singlets carry \(X = +1/3, -2/3, -5/3\) respectively. The new quark \(T\) has \(Q = 5/3\).
Some of the relevant LHC phenomenology is discussed in [7]. A refined mass estimate [8] for the bilepton is
\[ M(Y^{±±}) = (1.29 ± 0.06) \text{ TeV} \]
where faute de mieux it was assumed that the symmetry breaking of \( SU(3)_L \) is closely similar to that of \( SU(2)_L \). It will be pleasing if the physical mass is consistent with this.

3 New Quarks

Because the quarks are in triplets and anti-triplets of \( SU(3)_L \), rather than only in doublets of \( SU(2)_L \) as in the standard model, there is necessarily an additional quark in each family. In the first and second families they are the \( D \) and \( S \) respectively, both with charge \( Q = -4/3 \) and lepton number \( L = +2 \). In the third family is the \( T \) with charge \( Q = +5/3 \) and lepton number \( L = -2 \). All the three TeV scale quarks are colour triplets with spin-\( \frac{1}{2} \) and baryon number \( B = \frac{1}{3} \). Their masses are yet to be measured but may be expected to be below the ceiling of 4.1TeV which is the upper limit for symmetry breaking of \( SU(3)_L \) and probably above 1TeV. By analogy with the known quarks, one might expect \( M(T) > M(S) > M(D) \), although without experimental data this is conjecture.

The heavy quarks and antiquarks will be bound to light quarks and anti-quarks, and to each other, to form an interesting spectroscopy of mesons and baryons. Let us first display, in Tables 1, 2 the TeV mesons, then in Tables 3,4,5 the TeV baryons. The charge conjugate states are equally expected, and will reverse the signs of \( Q \) and \( L \).

4 Additional Baryons and Mesons

Although the \( Q \) masses are unknown, it may be reasonable first to make a preliminary discussion of these states by assuming that

\[ M(T) > M(S) + 2M_t > M(D) + 4M_t \]

where \( M_t \) is the top quark mass so that the lightest of the TeV baryons and mesons are those containing just one \( D \) quark or one \( \overline{D} \) antiquark. The
next lightest are the TeV baryons and mesons containing just one $S$ quark or one $\bar{S}$ antiquark.

We begin by discussing the decay modes of the $D\bar{q}$ mesons in Table 1, focusing on final states from the first family. The decays of $D$ include, taking care of $L$ conservation,

$$D \rightarrow d + Y^-$$
$$\rightarrow d + (e^- + \nu_e)$$
$$\rightarrow d + (\mu^- + \nu_\mu)$$
$$\rightarrow d + (\tau^- + \nu_\tau)$$

(7)
Table 3: TeV baryons $Qqq$

| $Q$ | $qq$ | $Q$ | $L$ |
|-----|------|-----|-----|
| $D/S$ | dd etc. | -2 | +2 |
| $D/S$ | ud etc. | -1 | +2 |
| $D/S$ | uu etc. | 0 | +2 |
| $T$ | dd etc. | +1 | -2 |
| $T$ | ud etc. | +2 | -2 |
| $T$ | uu etc. | +3 | -2 |

Table 4: TeV baryons $QQq$

| $QQ$ | $q$ | $Q$ | $L$ |
|------|-----|-----|-----|
| $(D/S)(D/S)$ | d etc. | -3 | +4 |
| $(D/S)(D/S)$ | u etc. | -2 | +4 |
| $(D/S)T$ | d etc. | 0 | 0 |
| $(D/S)T$ | u etc. | +1 | 0 |
| $TT$ | d etc. | +3 | -4 |
| $TT$ | u etc. | +4 | -4 |

which implies that decays of the $(D\bar{u})$ meson include

$$(D\bar{u}) \rightarrow \pi^- + (e^- + \nu_e)$$
$$\rightarrow \pi^- + (\mu^- + \nu_\mu)$$
$$\rightarrow \pi^- + (\tau^- + \nu_\tau)$$

(8)

and variants thereof where $\pi^-$ is replaced by any other non-strange negatively charged meson. The $d$ in Eq.(7) can be replaced by $s$ or $b$ which subsequently decay.
Table 5: TeV baryons \( QQ\bar{Q} \)

| \( QQ\bar{Q} \) | Q | L |
|----------------|---|---|
| \( (D/S)(D/S)(D/S) \) | -4 | +6 |
| \( (D/S)(D/S)T \) | -1 | +2 |
| \( (D/S)TT \) | +2 | -2 |
| \( TTT \) | +5 | -6 |

An alternative to Eq.(7) is

\[
D \rightarrow u + Y^{--} \\
\rightarrow u + (e^- + e^-) \\
\rightarrow u + (\mu^- + \mu^-) \\
\rightarrow u + (\tau^- + \tau^-)
\]

which implies additional decay modes of the \( (D\bar{u}) \) meson which include

\[
(D\bar{u}) \rightarrow \pi^0 + (e^- + e^-) \\
\rightarrow \pi^0 + (\mu^- + \mu^-) \\
\rightarrow \pi^0 + (\tau^- + \tau^-)
\]

(10)

and variants obtained by flavour replacements. Eqs.(8) and (10), and their generalisations to other flavours, suffice to illustrate the richness of \( (D\bar{u}) \) decays.

Turning to the meson \( D\bar{d} \), we can use Eq.(7) to identify amongst its possible decays

\[
(D\bar{d}) \rightarrow \pi^0 + (e^- + \nu_e) \\
\rightarrow \pi^0 + (\mu^- + \nu_\mu) \\
\rightarrow \pi^0 + (\tau^- + \nu_\tau)
\]

(11)
and variants thereof where \( \pi^0 \) is replaced by any other non-strange neutral meson. When \( u \) in Eq.(7) is replaced by \( c \) or \( t \) which subsequently decay, we arrive at many other decay channels additional to Eq.(11).

Employing instead the \( D \) decays in Eq.(9) implies additional decay modes of \( (D\bar{d}) \) meson that include

\[
(D\bar{d}) \rightarrow \pi^+ + (e^- + e^-) \\
\rightarrow \pi^+ + (\mu^- + \mu^-) \\
\rightarrow \pi^+ + (\tau^- + \tau^-)
\]

and variants obtained by flavour replacement. Eqs.(11) and (12), merely illustrate a few of the simplest \( (D\bar{d}) \) decays. There are many more.

Next we consider the lightest TeV baryons in Table 3 with \( Q = D \). Using the \( D \) decays from Eq.(7) we find for \( (Duu) \) decay

\[
(Duu) \rightarrow p + (l^-_i + \nu_i).
\] (13)

together with flavour rearrangements. Here, as in subsequent equations, \( i = e, \mu, \tau \).

Alternatively, the \( D \) decays from Eq.(9) lead to

\[
(Duu) \rightarrow N^{*++} + Y^{--}. \\
\rightarrow p + \pi^+ + (l^-_i + \nu_i).
\] (14)

Looking at the TeV baryon \( (Dud) \) the respective sets of decays corresponding to Eq.(7) are

\[
(Dud) \rightarrow n + (l^-_i + \nu_i)
\] (15)

where only the simplest light baryon is exhibited.

Corresponding to \( D \) decays in Eq.(9) there are also

\[
(Dud) \rightarrow p + (l^-_i + l^-_i)
\] (16)
in the simplest cases.

Finally, of the \((Dqq)\) TeV baryons, we write out the decays for \((Ddd)\), first for the \(D\) decays in Eq.\([7]\)

\[
(Ddd) \to N^* - + Y^- \\
\to n + \pi^- + (l_i^- + \nu_i).
\] (17)

within flavour variations.

With the Eq.\([9]\) decays of \(D\) there are also decays

\[
(Ddd) \to n + (l_i^- + l_i^-)
\] (18)

again with more possibilities by choosing alternative flavours.

We now replace the TeV quark \(D\) by the next heavier TeV quark \(S\) and repeat our study of decays whereupon we shall encounter the first example of decay not only to the known quarks but also to a TeV quark.

The TeV quark \(S\) has possible decay channels

\[
S \to d + Y^- \\
\to d + (e^- + \nu_e) \\
\to d + (\mu^- + \nu_\mu) \\
\to d + (\tau^- + \nu_\tau) \\
\to D + Z' \\
\to d + (e^- + \nu_e) + (e^+ + e^-) \\
\to d + (e^- + \nu_e) + (\mu^+ + \mu^-) \\
\to d + (e^- + \nu_e) + (\tau^+ + \tau^-) \\
\to d + (\mu^- + \nu_\mu) + (e^+ + e^-) \\
\to d + (\mu^- + \nu_\mu) + (\mu^+ + \mu^-) \\
\to d + (\mu^- + \nu_\mu) + (\tau^+ + \tau^-) \\
\to d + (\tau^- + \nu_\tau) + (e^+ + e^-) \\
\to d + (\tau^- + \nu_\tau) + (\mu^+ + \mu^-) \\
\to d + (\tau^- + \nu_\tau) + (\tau^+ + \tau^-)
\] (19)
where we note the opening up of channels due to $S \to D$ decay.

With Eq. (19) in mind, the decays of the TeV meson ($S\bar{u}$) include

\[
\begin{align*}
(S\bar{u}) &\to \pi^- + (l_i^- + \nu_i) \\
&\to \pi^- + (l_i^- + \nu_i) + (l_j^+ + l_j^-)
\end{align*}
\]  

(20)

where the second line involves a $D$ intermediary.

An alternative to Eq. (19) is

\[
S \to u + Y^{--} \\
\to u + (e^- + e^-) \\
\to u + (\mu^- + \mu^-) \\
\to u + (\tau^- + \tau^-)
\]  

(21)

which implies additional decay modes of ($S\bar{u}$)

\[
(S\bar{u}) \to \pi^0 + (l_i^- + l_i^-)
\]

(22)

and variants which replace $\pi^0$ by another neutral non-strange meson. Eqs. (20) and (22), illustrate sufficiently ($S\bar{u}$) decays.

Turning to the meson ($S\bar{d}$), we can use Eq. (19) to identify its possible decays

\[
(S\bar{d}) \to \pi^0 + (l_i^- + l_i^-)
\]  

(23)

When $u$ in Eq. (19) is replaced by $c$ or $t$ which subsequently decay, we arrive at many other decay channels additional to Eq. (23).

Employing instead the $S$ decays in Eq. (21) implies additional decay modes of ($S\bar{d}$) that include

\[
(S\bar{d}) \to \pi^+ + (l_i^- + l_i^-)
\]  

(24)

and variants obtained by flavour replacement. Eqs. (23) and (24), illustrate only a few of the simplest ($S\bar{d}$) decays. There are many more.
Next we consider the lightest TeV baryons in Table 3 with one $Q = S$. Using the $S$ decays from Eq. (19) we find for \((Suu)\) decay

\[(Suu) \rightarrow p + (l_i^- + \nu_i).\]  

(25)

together with flavour rearrangements.

Alternatively, the $S$ decays from Eq. (21) lead to

\[(Suu) \rightarrow N^{*++} + (l_i^- + l_i^-).. \]
\[\rightarrow p + \pi^+ + (l_i^- + l_i^-).\]  

(26)

Looking at the TeV baryon \((Sud)\) the respective sets of decays corresponding to Eq. (19) are

\[(Sud) \rightarrow n + (l_i^- + \nu_i)\]  

(27)

where only the simplest version is exhibited.

Corresponding to the $S$ decays in Eq. (21) there are the decays

\[(Sud) \rightarrow p + (l_i^- + l_i^-)\]  

(28)

For baryon \((Sdd)\), firstly from the $S$ decays in Eq. (19) we have

\[(Sdd) \rightarrow N^{*-} + Y^- \]
\[\rightarrow n + \pi^- + (l_i^- + \nu_i).\]  

(29)

within flavour variations.

Secondly, from the Eq. (21) decays of $S$ there are baryon decays of the type

\[(Sdd) \rightarrow n + (l_i^- + l_i^-)\]  

(30)

with more possibilities by choosing alternative flavours.
5 Discussion

We could continue further to study decays of all the baryons and mesons in our Tables. However, it seems premature to do so, until we know from experimental data the masses and mixings of $D$, $S$, $T$. We remark only that the type of lepton cascade which we have exhibited in Eq. (19) becomes ever more prevalent as the lepton number of the decaying hadron increases.

We may expect, by analogy with the top quark mass being close to the weak scale that the mass of the $T$ quark, although probably below 4.1 TeV for the symmetry-breaking reason discussed at supra, might be not much below. For example it might exceed 3 TeV whereupon the mass of a $(T T T)$ baryon could exceed 9 TeV. Since this baryon has high lepton number, it must be pair produced and such production is far beyond the reach of the 14 TeV LHC. Its study would require a 100 TeV collider of the type presently under preliminary discussion. As a foretaste of the physics accessible to such a hypothetical collider, the simplest decay of the $(T T T)$ baryon we can find is

$$p + 4(e^+) + 2(\bar{\nu}_e).$$

which would be very exciting to confirm.

At the time of writing, the particles exhibited in our Tables are conjectural. After the bilepton is discovered the existence of all the additional baryons and mesons in our five Tables would become a sharp predictions.

The bilepton resonance in $\mu^+\mu^-$ has been the subject of searches by the ATLAS and CMS Collaborations at the LHC, starting in March 2021. In March 2022, ATLAS published an inconclusive result [9] about the existence of the resonance, putting only a lower mass limit $M_Y > 1.08$ TeV. CMS has better momentum resolution and, what is the same thing, charge identification than ATLAS and should be able to investigate the bilepton resonance proper. The high sensitivity of CMS is a result of serendipity because it was designed in 1993 not for the bilepton but to search for heavy Z-primes[11]. A second serendipity was an accidental 2015 meeting in London between us and Sir Tejinder Virdee who helped design the CMS detector.

Our strong belief in the existence of the bilepton lies partly in the close relationship between the 1961 paper[10] which solved the parity puzzle and our 1992 paper[1] which solved the family puzzle. We regard these two papers which span three decades as well-matched bookends,
According to our calculations [7], the Run 2 data with 139/fb collected by 2018 are sufficient for a CMS discovery of the bilepton. If not, future LHC runs up to their target integrated luminosity of 4/ab can provide 28 times as many events and bilepton discovery would be merely postponed. We do hope, however, that a great discovery will be made by the LHC within six months from today (July 25, 2022).

*Note added:*
We answer here one interesting question received after our talk: Why are these heavy states not as unstable as the top quark which lives for less than a trillion trillionth of a second? The answer is that they decay via bilepton exchange. This fact renders their lifetimes a trillion times longer than the top quark lifetime.

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