BILEPTONS - STATUS AND PROSPECTS

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ABSTRACT

The theoretical background for bileptonic gauge bosons is reviewed, both the SU(15) GUT model and the 3-3-1 model. Then the mass limits for bileptons are discussed coming from $e^+e^-$ scattering, polarized muon decay and muonium-antimuonium conversion. A consequence of precision electroweak data on the masses is mentioned. Discovery in $e^-e^-$ at a linear collider is emphasized.

Theoretical Background.

The simplest grand unified theory (GUT) is SU(5) where each family is $(10 + \bar{5})_L$. The gauge bosons mediate proton decay with (in the minimal form) too fast a rate. The gauge bosons have no definite $B$ or $L$, only $(B - L)$ which is conserved.

SU(15) arose from the idea of having unification where the gauge bosons have well-defined $B$ (and $L$) and so do not mediate proton decay. Each family is assigned to a $15$ of SU(15); each of the $224$ gauge bosons then have a definite $B$ and $L$. Hence proton decay is absent in the gauge sector.

The first stage of symmetry breaking takes SU(15) to $SU(12)_q \times SU(3)_l$ at a GUT scale $M_G$. $SU(3)_l$ acts on the lepton triplet $(e^+, \nu_e, e^-)$ and contains the SU(2) doublet of gauge bosons $(Y^{--}, Y^{-})$ and the antiparticles $(Y^{++,} Y^{+})$. These bileptons have a mass at or just above the weak scale, say in the region 300 GeV to 600 GeV (this can be made more rigorous). In particular, the idea that a narrow resonance might appear in $e^-e^- \rightarrow \mu^-\mu^-$ was suggested in [1]. The width is predicted as a few per cent of the mass.

The anomaly cancellation of SU(15) is inelegant: by mirror fermions. This is an aesthetic consideration - not a phenomenological one. Nevertheless, it is interesting to know that there is a chiral model which incorporates the bileptons.

To introduce the 331 Model[2] the following are motivating factors:

i) Consistency of a gauge theory (unitarity, renormalizability) requires anomaly cancellation. This requirement almost alone is able to fix all electric charges and other quantum numbers within one family of the standard model. This accounts for charge quantization, e.g. the neutrality of the hydrogen atom, without the need for a GUT.

ii) This does not explain why $N_f > 1$ for the number of families but is sufficiently impressive to suggest that $N_f = 3$ may be explicable by anomaly cancellation in an extension of the standard model. This requires that each extended family have non-vanishing anomaly and that the three families are not all treated similarly.

iii) A striking feature of the mass spectrum in the SM is the top mass suggesting the 3rd. family be treated differently and that the anomaly cancellation be proportional to: $+1 +1 -2 = 0$.

iv) There is an "-2" lurking in the SM in the ratio of the quark electric charges!
v) The electroweak gauge group extension from $SU(2)$ to $SU(3)$ will add five gauge bosons. The adjoint of $SU(3)$ breaks into $8 = 3 + (2 + 2) + 1$ under $SU(2)$. The 1 is a $Z'$ and the two doublets are readily identifiable from the leptonic triplet or antitriplet $(e^-, \nu_e, e^+)$ as bilepton gauge bosons $(Y^-, Y^-)$ with $L = 2$ and $(Y^+, Y^+)$ with $L = -2$. Such bileptons appeared first in stable-proton GUTs but there the fermions were non-chiral and one needed to invoke mirror fermions; this is precisely what is avoided in the 331 Model. But it is true that the $SU(3)$ of the 331 Model has the same couplings to the leptons as that of the leptonic $SU(3)_L$ subgroup of $SU(15)$ which breaks to $SU(12)_q \times SU(3)_l$.

Now I am ready to introduce the 331 Model in its technical details: the gauge group of the standard model is extended to $SU(3) \times SU(3) \times U(1)$ where the electroweak $SU(3)$ contains the standard $SU(2)$ and the weak hypercharge is a mixture of $\lambda_8$ with the $U(1)$. The leptons are in the antitriplet $(e^-, \nu_e, e^+)_L$ and similarly for the $\mu$ and $\tau$.

These antitriplets have $X = 0$ where $X$ is the new $U(1)$ charge. This can be checked by noting that the $X$ value is the electric charge of the central member of the triplet or antitriplet.

For the first family of quarks I use the triplet $(u, d, D)_L$ with $X = -1/3$ and the right-handed counterparts in singlets. Similarly, the second family of quarks is treated. For the third family of quarks, on the other hand, I use the antitriplet $(T, t, b)_L$ with $X = +2/3$. The new exotic quarks $D$, $S$, and $T$ have charges $-4/3$, $-4/3$ and $+5/3$ respectively.

It is instructive to see how this combination successfully cancels all chiral anomalies:

The purely color anomaly $(3_L)^3$ cancels because QCD is vector-like.

The anomaly $(3_L)^3$ is non-trivial. Taking, for the moment, arbitrary numbers $N_c$ of colors and $N_l$ of light neutrinos I find this anomaly cancels only if $N_c = N_l = 3$.

The remaining anomalies $(3_c)^2 X, (3_L)^2 X, X^3$ and $X(T^2_{\mu\nu})$ also cancel.

Each family separately has non-zero anomaly for $X^3, (3_L)^2 X$ and $(3_L)^3$; in each case, the anomalies cancel proportionally to $+1 + 1 - 2$ between the families.

To break the symmetry I need several Higgs multiplets. A triplet $\Phi$ with $X = +1$ and VEV $< \Phi > = (0, 0, U)$ breaks 331 to the standard 321 group, and gives masses to $D$, $S$, and $T$ as well as to the gauge bosons $Y$ and $Z'$. The scale $U$ sets the range of the new physics and I shall discuss more about its possible value.

The electroweak breaking requires two further triplets $\phi$ and $\phi'$ with $X = 0$ and $X = -1$ respectively. Their VEVs give masses to $d$, $s$, $t$ and to $u$, $c$, $b$ respectively. The first VEV also gives a contribution of an antisymmetric-in-family type to the charged leptons. To complete a satisfactory lepton mass matrix necessitates adding a sextet with $X = 0$.

What can the scale $U$ be? It turns out that there is not only the lower bound expected from the constraint of the precision electroweak data, but also an upper bound coming from a group theoretical constraint within the theory itself.

The lower bound on $U$ from $Z - Z'$ mixing can be derived from the diagonalization of the mass matrix and leads to $M(Z') \geq 300 GeV$. The limit from FCNC (the Glashow - Weinberg rule is violated) gives a similar bound; here the suppression is helped by ubiquitous $(1 - 4\sin^2\theta)$ factors.

In these considerations, particularly with regard to FCNC, the special role played by the third family is crucial; if either of the first two families is the one treated asymmetrically the FCNC disagree with experiment.
The upper bound on $U$ arises because the embedding of the standard 321 group in 331 requires that $\sin^2 \theta \leq 1/4$. When $\sin^2 \theta = 1/4$, the $SU(2) \times U(1)$ group embeds entirely in $SU(3)$, and the coupling of the $X$ charge in principle diverges. Because the phenomenological value is close to 1/4 - actually $\sin^2(M_Z) = 0.233$ - the scale $U$ must be less than about $3TeV$ after scaling $\sin^2(\mu)$ by the renormalization group. Putting some reasonable upper bound on the $X$ coupling leads to an upper bound on the bilepton mass, for this 331 Model, of about 800GeV [Here I have allowed one further Higgs multiplet - an octet].

**Allowed Masses**

In order to set limits on the minimum mass allowed by the experimental data, a number of processes were considered initially. At the time (1992), as now, the most accurate high-energy data on the planet came from LEP. Analysis of $e^+e^-$ scattering at LEP was used to give a lower limit of about 120GeV on the singly-charged bilepton, from the fact that its exchange in the u-channel effects angular distributions observed. This limit which did seem surprisingly weak was the best found at the time.

The most useful experiment for limiting the singly-charged bilepton mass from below is polarized muon decay. This is an example where a very low energy experiment with sufficient precision can compete successfully with the highest energy experiments in limiting the possible properties of the highest accessible mass particles. With the coupling parametrized as $V - \xi A$ where $\xi$ is a Michel parameter, the present limit on $\xi$ is $1 \geq \xi \geq 0.997$ coming from about $10^6$ examples of the decay. This leads to a lower bound $M(Y^\pm) \geq 230$GeV for the singly-charged bilepton, from this direct measurement. Since

$$(1 - \xi) \sim (M_W/M_Y)^4$$

I deduce that if $(1 - \xi)$ could be measured to an accuracy of $10^{-4}$ the limit would become $M_Y \geq 10M_W$ and if to an accuracy $10^{-8}$ it would be $M_Y \geq 100M_W$. The first of these is within the realm of feasibility and certainly seems an important experiment to pursue. The group at the Paul Scherrer Institute near Zurich (Gerber, Fetscher) is one that is planning this experiment.

A new limit since the previous Santa Cruz $e^-e^-$ workshop in 1995 comes from muonium-antimuonium conversion which provides a lower limit $M(Y^{\pm\pm}) > 360$GeV on the doubly-charged bilepton.

By studying the $S$ and $T$ parameters which measure the compatibility of theory with high precision experiment, it can be shown that given the lower mass bound on the doubly-charged bilepton, the singly-charged bilepton must have a mass $M(Y^\pm) > 320$GeV, a tighter bound than the direct measurement.

The upper mass limit from the theory with minimal Higgs in the 331-model, is $M(Y^\pm, Y^{\pm\pm}) < 600$GeV. As mentioned above, if one extends the Higgs structure by adding an octet of $SU(3)_L$ this limit relaxes to $M(Y^\pm, Y^{\pm\pm}) < 800$GeV. So this is somewhat model-dependent.

A careful analysis of all the mass limits on bileptons has been carried out in the last year by Cuypers.

The crucial question is how to produce the bilepton in experiment. The bilepton can be produced in a hadron collider such as a $pp$ or $p\bar{p}$ machine, or in a lepton collider such as $e^+e^-$ or $e^-e^-$. For the hadron collider the $Y$ may be either pair produced or produced in association with an exotic quark [the latter carries $L = \pm 2$]. It turns out that the
associated production is about one order of magnitude larger. These cross-sections are calculated in the literature - for a pp collider of the type envisioned there would be at least $10^4$ striking events per year.

Surely the most dramatic way to spot a bilepton, however, would be to run a linear collider in the $e^-e^-$ mode and find a direct-channel resonance. A narrow spike at between $300\text{GeV}$ and $1000\text{GeV}$ would have a width at most a few percent of its mass and its decay to $\mu^-\mu^-$ has no standard model background.

The discovery of such a bileptonic gauge boson will strongly suggest that the electroweak isospin $SU(2)$ is to be regarded as a subgroup of $SU(3)_L$. The situation can be regarded as roughly analogous to the extension of nuclear isospin to the flavor $SU(3)$; the bileptons play the role in that analogy of the K meson doublets filling out the adjoint octet of $SU(3)$. The shortcoming of that analogy (unfortunately!) is that there the strange particles had been already discovered before the theory was extended.

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