$Z^0 \rightarrow b\bar{b}$ Excess from R-Parity Violation

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**Abstract**

The $Z^0 \rightarrow b\bar{b}$ excess, $Z^0 \rightarrow c\bar{c}$ deficit, and low left-right asymmetry $A_b$ may be explained by a single term $\lambda C^c B^c B'^e$ in the superpotential. This operator violates R-parity and requires a sequential 4th generation. 1-loop diagrams involving squark exchange interfere with the tree-level processes to give an excess of right-handed $b$ quarks, and a deficit of right-handed $c$ quarks. Though the coupling must be large ($\lambda \approx 2$ or 3), the model is phenomenologically and cosmologically acceptable.
1 Some Curious Data

Though the Standard Model has enjoyed great experimental success, we may be seeing the first signs of new physics in the decay modes of the $Z^0$ boson. Combined LEP and SLC data\cite{1} indicate a 3\% excess of $Z^0 \rightarrow b \bar{b}$ decays over the Standard Model prediction. They also hint that the extra $b$’s are right-handed, and are offset by a corresponding deficit of $c$’s. The data are:

$$R_b \equiv \frac{\Gamma(Z^0 \rightarrow b \bar{b})}{\Gamma(Z^0 \rightarrow \text{hadrons})} = 0.2219 \pm 0.0017 \quad (R^{SM}_b = 0.2156)$$

$$R_c \equiv \frac{\Gamma(Z^0 \rightarrow c \bar{c})}{\Gamma(Z^0 \rightarrow \text{hadrons})} = 0.1540 \pm 0.0074 \quad (R^{SM}_c = 0.1724)$$

$$R_l \equiv \frac{\Gamma(Z^0 \rightarrow \ell \bar{\ell})}{\Gamma(Z^0 \rightarrow \text{hadrons})} = 20.788 \pm 0.032 \quad (R^{SM}_l = 20.786)$$

$$A_b \equiv \frac{\Gamma(Z^0 \rightarrow b_L \bar{b}_L) - \Gamma(Z^0 \rightarrow b_R \bar{b}_R)}{\Gamma(Z^0 \rightarrow b_L \bar{b}_L) + \Gamma(Z^0 \rightarrow b_R \bar{b}_R)} = 0.841 \pm 0.053 \quad (A^{SM}_b = 0.935)$$

$$A_c = 0.606 \pm 0.090 \quad (A^{SM}_c = 0.667)$$

(The SM prediction for $R_l$ assumes $\alpha_s = 0.123$ and $m_t = 180$ GeV.) The discrepancy (“crisis”) in $R_b$ is particularly significant, a 3.7\sigma effect.

2 Our Model, and Its Implications

We propose a supersymmetric model to explain these data. It is the MSSM plus the additional R-parity violating term

$$\lambda \epsilon^{abc} C^c_a B^c_b B'^c_c$$

in the superpotential, where \{a, b, c\} are color indices. $C^c$, $B^c$, and $B'^c$ are superfields representing left-handed antiquarks (or right-handed quarks) and their scalar superpartners. $C$ is charm, $B$ is bottom, and $B'$ is the down-type quark in a sequential 4th generation. The coupling must be fairly large ($\lambda \approx 2$ or 3).

The MSSM corrections to $R_b$, etc., are known to be insignificant: $\delta R_b < 0.002$ \cite{4} in the experimentally allowed region of parameter space, essentially because the sparticles must be heavy and therefore decouple. (See \cite{3}, however, for a clever twist on a 4-generation SUSY model). We will therefore only calculate corrections from our new term. We are able to evade sparticle decoupling by giving $b'$ a mass comparable to the squark masses.

A sequential 4th generation will give acceptable values of the Peskin-Takeuchi parameters ($S, T, U$) as long as $t'$ and $b'$ are nearly degenerate. Our model does not suffer from the large FCNC’s that come with “exotic” 4th generations. Of course, we need $m_{\nu} > M_Z/2$.

Our term violates baryon number, but not lepton number. Thus it cannot induce proton decay. Neutron oscillation is highly suppressed by at least 4 loops and several small CKM
angles (since our term does not involve the first generation), and a factor $\Lambda_{QCD}^2/\tilde{m}^4M_{\tilde{g}}$ (where $\tilde{m}$ is the squark mass and $M_{\tilde{g}}$ is the gluino mass [9]); we estimate an effect roughly 7 orders of magnitude weaker than the experimental limit ($\tau_{\tilde{m}} > 1.2 \times 10^8$ s).

Dreiner and Ross [9] showed that commonly quoted cosmological bounds [6] can be avoided. In the presence of our new interaction and of sphalerons, there are still 3 conserved quantities ($L_1 - L_2$), $(L_1 - L_3)$, and $(L_1 - L_4)$ (though $m_\nu$ may break the latter). A GUT-generated asymmetry in any of these is preserved. Near the electroweak phase transition, sphalerons translate this primordial lepton flavor asymmetry into a baryon asymmetry.

The large coupling $\lambda$ and the 4th-generation Yukawas contribute positively $(dm^2/dt > 0)$ to the running of scalar masses [7]. This effect is tamed if we have a heavy gluino, e.g.

$$\frac{d\tilde{m}_{Bc}^2}{dt} = \frac{2\lambda^2}{8\pi^2} \left[ \tilde{m}_{Bc}^2 + \tilde{m}_{\nu c}^2 + m_{\nu c}^2 + A^2 \right] + \frac{3\lambda_{\nu}^2}{8\pi^2} \left[ \tilde{m}_{Bc}^2 + \tilde{m}_{B\nu}^2 + m_{\nu c}^2 + A^2 \right] - \frac{2}{\pi} \left[ \frac{4\alpha_3}{3} M_3^2 + \frac{\alpha_1}{15} M_1^2 \right]$$

(3)

where $\lambda_{\nu} = \sqrt{2} m_{\nu}/v$, $A$ is the trilinear soft breaking coefficient, and $M_3$ ($M_1$) is the gluino (bino) mass. (In SUSY GUT’s, the gaugino masses unify $M_4(M_G) = M_0$, and run like $\alpha_i$, so the gluino is naturally the heaviest one with $M_3 = 2.9 M_0$.)

The running of $\lambda_{\nu}$ and $\lambda_{\nu}$ is discussed in [8], where an upper bound $m_{\nu} < 156$ GeV is given to keep the couplings perturbative up to a GUT scale. The running of $\lambda$ is given by

$$\frac{d\lambda}{dt} = \beta(\lambda) = \frac{\lambda}{16\pi^2} \left[ 6\lambda^2 + 2\lambda_{\nu}^2 - 8g_3^2 - \frac{4}{5} g_1^2 \right]$$

(4)

(with $g_1^2 = \frac{5}{3} g_2^2$). Since we will need $\lambda^2(M_Z) > 4.6$, $\lambda$ exhibits a Landau pole at or below $30 M_Z = 2.7$ TeV. Perturbative unification is thus not possible unless some new physics enters at this scale.

3 The 1-Loop Diagrams

The $Z^0 \rightarrow b\bar{b}$ excess arises from interference between the tree-level diagram and the 1-loop diagrams shown in Fig. [8] (plus 3 others related by $c \leftrightarrow b'$, but these are small). Since only the $B^c$ superfield enters, only right-handed $b$ production is affected. The calculation can be found in [8], eqs.79,82. We use the approximation $\{m_{\nu}, \tilde{m}_{\nu c}\} \gg M_Z$, which we find agrees to better than 10% with exact numerical calculations even for $\tilde{m}_{\nu c} = M_Z$. In this approximation, the Standard Model tree-level coupling $g_{bR}^b = s_W^2/3$ is modified by

$$\delta g_R^b = \frac{2|\lambda|^2}{16\pi^2} (g_R^{b'} - g_L^{b'}) \mathcal{F} \left( \frac{m_{\nu}^2}{m_{\nu c}^2} \right), \quad \mathcal{F}(r) = \frac{r}{(r-1)^2} (r-1-\ln r)$$

(5)

$\mathcal{F}(r)$ is positive and monotonically increasing, with $\mathcal{F}(0) = 0$ (satisfying the decoupling theorem as the squark gets heavy), and an asymptotic value $\mathcal{F}(\infty) = 1$.
Note that \((g_R^b - g_L^b) = -T_3^b = \frac{1}{2}\). The fact that this has the same sign as \(g_R^b = s_W^2/3\) gives an enhancement of \(b\) production. (In any model of this kind, the heavy fermion must have \(T_3 < 0\) to give the right sign for \(\delta R_b\).) We get the right magnitude by setting \(\lambda^2 \mathcal{F} = 4.6\), so we need a \(\lambda \approx 2\) or 3.

\[
\begin{align*}
\text{Fig. 1: 1-loop diagrams.}
\end{align*}
\]

Analogously, the right-handed charm coupling \(g_R^c = -2s_W^2/3\) is modified by

\[
\delta g_R^c = \frac{2|\lambda|^2}{16\pi^2} (g_R^c - g_L^c) \mathcal{F} \left( \frac{m_b^2}{\tilde{m}_{bc}^2} \right) \tag{6}
\]

The magnitude of the charm coupling is reduced, giving a \(c\) deficit.

4 Squark Masses

If squarks are degenerate, the \(c\) deficit is fixed to be twice the \(b\) excess. Choosing only the single parameter \(\lambda\) would then give

\[
R_b = .2219 \text{ (set), } \quad R_c = .1625, \quad R_l = 20.68, \quad A_b = .89, \quad A_c = .77 \tag{7}
\]

The total hadronic width \((R_l)\) is too low (unless \(\alpha_s(M_Z) \approx .15\), which seems unlikely).

Thus we need to take \(\tilde{m}_{bc} > \tilde{m}_{cc}\). We can adjust the squark masses to leave the total hadronic width unaltered (so \(R_l = R_l^{SM}\) with \(\alpha_s(M_Z) = .123\)), giving the predictions

\[
R_b = .2219 \text{ (set), } \quad R_c = .1656, \quad A_b = .88, \quad A_c = .73 \tag{8}
\]

The value of \(A_c\) is still a bit high, but only by 1.4\(\sigma\). These results are in good statistical agreement with all the data.

5 Some Variations: \(R_b\) Only

One could treat the \(c\) deficit as experimental error, and only explain the (right-handed) \(b\) excess, which under this assumption becomes

\[
R_b = .2205 \pm .0016 \quad (R_b^{SM} = .2156) \tag{9}
\]

We can do this with a superpotential term \(\lambda e^{abc} T_a^c B_b^c B_c^c\) (to replace eq. [2]) as long as \(m_{\nu} > m_t\).
The same result can be achieved with a superpotential term $\lambda Q'B'B'$, with $Q' = (T', B')$ and $L' = (\nu', \tau')$, if $\tau'$ (or $b'$) is the heaviest 4th generation fermion. This term has the phenomenological (and cosmological) advantage of violating only $L_4$, not $B$.

Yet another possibility is $\lambda Q_3 B'L'$, with $Q_3 = (T, B)$. Then a small $b_L$ deficit in addition to the $b_R$ excess drives $A_b$ even lower.

6 Conclusions

Data indicate an excess of right-handed $b$'s in $Z^0$ decays, offset by a deficit of $c$'s. Our model explains these using a single $R_P$-violating term $\lambda C^c B'^c$ in the superpotential. Choosing $\lambda$ appropriately, and requiring $\tilde{m}_{B'^c} > \tilde{m}_{C^c}$, we can achieve agreement with the data to $1.6\sigma$ or better.

We wish to thank Nima Arkani-Hamed, Hsin-Chia Cheng, Lawrence J. Hall, Richard Holman, Stephen Hsu, and Martin Savage for helpful discussions. This work was partially supported by the U.S. Dept. of Energy under Contract DE-FG02-91-ER40682.

References

[1] LEP Electroweak Working Group, CERN-PPE/95-172 (Nov. 1995) eq. (13); J. Huber (for SLD), SLAC-PUB-95-7019 (July 1995).

[2] A. Djouadi et al., Nucl. Phys. B349:48 (1991); M. Boulware & D. Finnell, Phys. Rev. D44:2054 (1991); G. Altarelli, R. Barbieri & F. Caravaglios, Phys. Lett. B314:357 (1993); D. García, R.A. Jiménez & J. Solá, Phys. Lett. B347:321 (1995) [E: B351:602 (1995)]; G.L. Kane, R.G. Stuart & J.D. Wells, Phys. Lett. B354:350 (1995); J.D. Wells & G.L. Kane, Phys. Rev. Lett. 76:869 (1996); E. Ma & D. Ng, Phys. Rev. D53:255 (1996); X. Wang, J.L. Lopez & D.V. Nanopoulos, Phys. Rev. D52:4116 (1995); J. Ellis, J.L. Lopez & D.V. Nanopoulos, CERN-TH/95-314, hep-ph/9512288.

[3] M. Carena, H.E. Haber & C.E.M. Wagner, CERN-TH/95-311, hep-ph/9512446.

[4] F. Zwirner, Phys. Lett. B132:103 (1983); R. Mohapatra, Nucl. Inst. & Meth. A284:1 (1989).

[5] H. Dreiner & G.G. Ross, Nucl. Phys. B410:188 (1993).

[6] B.A. Campbell, S. Davidson, J. Ellis & K.A. Olive, Phys. Lett. B256:457 (1991); W. Fischler, G. Giudice, R.G. Leigh & S. Paban, Phys. Lett. B258:45 (1991).

[7] L. Alvarez-Gaumé, J. Polchinski & M.B. Wise, Nucl. Phys. B221:495 (1983); M. Claudson, L. Hall & I. Hinckliffe, Nucl. Phys. B228:501 (1983).

[8] J.F. Gunion, D.W. McKay & H. Pois, Phys. Lett. B334:339 (1994).

[9] P. Bamert et al., McGill-96/04, hep-ph/9602438.