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$Z^0 \rightarrow N_4 \bar{\nu} \rightarrow$ Monojet*

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ABSTRACT

We discuss flavor-changing Z decays involving a heavy fourth generation neutrino with mass bigger than $M_Z/2$.

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1. INTRODUCTION

Historically, charged leptons have been the first particles to be discovered in each new generation. The charged leptons are lighter than the corresponding quarks, and they give clear signals in detectors. But if the fourth generation neutrino is massive and decays, it may well be the first to be discovered among the fourth generation members.

With this motivation, I would like to discuss fourth generation neutrinos which can be produced from on-shell Z^0 decays at the SLC or LEP. Let me refer to neutrinos as heavy or light depending on whether the mass is larger or smaller than half of the mass of the Z^0, and let N denote the heavy neutrino.

2. LIGHT NEUTRINOS

The production rate of light neutrinos from Z^0 decay is

$$\frac{\Gamma(Z^0 \to \nu_4 \overline{\nu_4})}{\Gamma(Z^0 \to \nu\overline{\nu})_{|m_\nu=0}} = \begin{cases} \frac{1}{4}\beta(3+\beta^2) & \text{Dirac} \\ \beta^3 & \text{Majorana} \end{cases} \tag{2.1}$$

where $\beta^2 = 1 - 4m_4^2/M_Z^2$. These neutrinos can be searched for by the increased Z^0 width these decays cause, and more directly by tagging Z^0 decays through detection of the bremsstrahlung photon in the process of $e^+e^- \to \gamma\, Z^0 \to \gamma\, \bar{\nu}\nu$. If the neutrino is unstable and decays in the detector, we will be able to see a double vertex.

3. HEAVY NEUTRINOS

Since in this case, N is assumed to be heavier than half of the Z^0 mass, $N(\overline{N})$ can be produced, not in pairs, but only in association with a light neutrino $\overline{\nu}(\nu)$. Because in the standard model the neutral current is diagonal in flavor at tree level (GIM mechanism), this flavor-changing process can occur only through diagrams involving loops. In these loop calculations, the Higgs content (which determines the type of the mass of the neutrino) needs to be specified. Here we assume the following. The gauge group is the standard $SU(2)_L \times U(1)$. The standard Higgs doublet implements the spontaneous symmetry breaking mechanism and also generates Dirac masses for all the fermions, including the neutrinos. The field content of the lepton sector is given as follows:

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L \quad \begin{pmatrix}\nu_L\\ L\end{pmatrix}_L$$

$$\begin{array}{cccc} \nu_{1R} & \nu_{2R} & \nu_{3R} & \nu_{4R} \\ e_R & \mu_R & \tau_R & L_R \end{array} \tag{3.1}$$

where

$$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i \qquad \begin{cases} \alpha = e, \mu, \tau, L & \text{gauge eigenstate index} \\ i = 1, 2, 3, 4 & \text{mass eigenstate index} \end{cases} \tag{3.2}$$

$N \equiv \nu_4$ (heavy), and U is a unitary mixing matrix. We look at the process at one loop level, where the relevant diagrams in the unitary gauge are shown in Fig. 1.

4. THE CALCULATION OF $Z^0 \rightarrow \nu\overline{N}$ or $\overline{\nu}N$

We can quickly estimate the partial decay width as

$$\frac{\Gamma_i(Z^0 \rightarrow N\overline{\nu_i})}{\Gamma(Z^0 \rightarrow \nu\overline{\nu})_{|m_\nu=0}} \simeq \left(\frac{g^2}{16\pi^2}\right)^2 \left(\sum_{\alpha=e}^{L} U^*_{\alpha N} U_{\alpha\nu_i} \frac{m_\alpha^2}{M_W^2}\right)^2 \tag{4.1}$$

The factor g^2 is from two extra vertices, $1/16\pi^2$ is a factor one gets from the integral over loop-momentum, and the charged lepton mass factor is due to the coupling of the longitudinal mode of the W to fermion masses. Because the first factor is about 2×10^{-5}, an appreciable production rate can come only when the mass of the heavy charged lepton is much bigger than M_W. The contribution from the light charged leptons can be ignored.

The present experimental upper bounds on the light neutrino masses are known to be[1-3] $m_{\nu_e} \leq 18eV$, $m_{\nu_\mu} \leq 250\ KeV$, and $m_{\nu_\tau} \leq 70\ MeV$, which are all very light compared to m_N. So neglecting the masses of the light neutrinos, the effective $\nu_i\overline{N}$ neutral current is

$$\epsilon \cdot J = \overline{\nu_i}_L \left(\epsilon \cdot \gamma F_E + \frac{q \cdot \gamma}{M_Z} \epsilon \cdot \gamma F_M\right) N, \tag{4.2}$$

where ϵ and q are the polarization and momentum vectors of Z^0. The decay rate that follows from Eq. (4.2) is

$$\Gamma_i(Z^0 \rightarrow N\overline{\nu_i}) = \frac{M_Z}{48\pi}(1 - z^2)^2(|F_E|^2(2 + z^2) + 6Re(F_E F_M^*)z + |F_M|^2(1 + 2z^2)), \tag{4.3}$$

where $z \equiv m_N/M_Z$. The form factors F_E and F_M are helicity-preserving and helicity-flipping, respectively. We need to compute[4] the diagrams in Fig. 1 to obtain F_E and F_M. It's well known that the dimensional regularization method is the simplest to use for weak interaction loop calculations, and the apparent incompatibility of the chirality of the theory and the generalized dimension of the regularization scheme can be overcome operationally by using the convention $\{\gamma_5, \gamma_\mu\} = 0$. The loop integrals can be expressed in terms of elementary functions, i.e., polynomials, logarithmic functions and Spence functions (bilogarithmic functions)[5] . One can show the decay amplitude is divergence free in the general linear gauge. Unfortunately, the expression of the amplitude in the general case in terms of elementary functions is so long that a computer is needed to evaluate the expression. Fig. 2 shows a result of the full calculation at $M_N \sim 51 GeV$. The cusp is due to the effect of the threshold. F_M is proportional to M_N, and small compared to F_E. In the asymptotic limit, $m_L^2 \to \infty$, $F_M = 0$ and F_E becomes independent of the electric charges of fermions. Therefore all fermions have the same asymptotic behavior, and we have checked that our result agreed with the calculation in the quark sector.[6]

$$\frac{\Gamma_i(Z^0 \to N\overline{\nu_i})_{m_L^2 \to \infty}}{\Gamma(Z^0 \to \nu\overline{\nu})_{|m_\nu = 0}} = \left(\frac{g^2}{16\pi^2}\right)^2 \left(U_{LN}^* U_{L\nu_i} \frac{m_L^2}{M_W^2}\right)^2 \tag{4.4}$$

The asymptotic value (as $m_L^2 \to \infty$) of Eq.(4.4) at $M_N = 51 GeV$ are shown by the dash-dot line in Fig. 2.

There have been similar calculations for quarks[7] and charged leptons.[8] Because of the "symmetry" between the quark sector and lepton sector, the calculations for $\Gamma(Z^0 \to \nu\bar{N})$ and $\Gamma(Z^0 \to q\bar{Q})$ are almost identical. A little difference comes from the different electric charges, and the color degrees of freedom enhances the quark production rate by a factor of 3.

5. THE NUMBER OF THE HEAVY NEUTRINOS FROM Z^0.

Since $U_{LN} \sim 1$, then $|U_{L\nu_i} U^*_{LN}|^2 \sim |U_{L\nu_i}|^2$. Then the total production rate of heavy neutrinos is

$$\Gamma = \sum_i 2\Gamma_i, \tag{5.1}$$

which is proportional to $\sum_i |U_{L\nu_i}|^2$ $(\equiv \theta^2)$. Table 1 shows the number of heavy neutrinos which can be produced from 10^6 Z^0's for different charged lepton masses m_L and mixing angles θ.

	m_L	
θ	500 GeV	200 GeV
0.22	32	0.9
0.05	2.7	0.053

Table 1: The number of the heavy neutrinos from 10^6 Z^0's.

6. MONOJET SIGNATURE

Since the light neutrino will be unobserved, the decay of a heavy neutrino will have the signature of a monojet. Depending on the lifetime of the heavy neutrino, we may be able to see a striking signature. So let us look at the lifetime of the heavy neutrino. Fig. 3 shows the decay diagram. Because of the GIM mechanism, the Z^0 exchange diagram does not contribute to the decay.

The heavy neutrino decay process is essentially the same as μ decay,

$$\frac{\Gamma(N \to \ell_\alpha^- e^+ \nu)}{\Gamma(\mu \to e\overline{\nu}\nu)} = \frac{m_N^5}{m_\mu^5} |U_{\alpha N}|^2. \tag{6.1}$$

The total decay width of the heavy neutrino can be obtained by including all the degrees of the freedom in $N \rightarrow \ell_\alpha f_1 \overline{f_2}$ (top is not included).

$$\Gamma_N \simeq 9 \; \frac{m_N^5}{m_\mu^5} \, \Gamma_\mu \;\; \sum_\alpha |U_{\alpha N}|^2 \tag{6.2}$$

Therefore the lifetime of the heavy neutrino is

$$\tau_N \simeq \frac{\tau_\mu \;\; m_\mu^5}{9 \; m_N^5 \;\; (\sum_\alpha |U_{\alpha N}|^2)} \simeq 10^{-22} \; \frac{M_Z^5}{m_N^5} \; \left(\sum_\alpha |U_{\alpha N}|^2 \right)^{-1} \; \text{sec} \tag{6.3}$$

For any mixing angles for which there will be a detectable number of $Z^0 \rightarrow N\bar{\nu}$ decays, the lifetime of the heavy neutrino is extremely small, and the decay not separable from the production vertex. Therefore if a heavy neutrino is to be observed, the signal is a monojet - a jet of decay particles into one hemisphere with the other hemisphere empty.

FIGURE CAPTIONS

1. Fig. 1. Feynman diagrams for $Z^0 \rightarrow N\bar{\nu}$ in the unitary gauge.
2. Fig. 2. The production rate of heavy neutrinos($m_N > M_Z/2$) from Z^0 decay.
3. Fig. 3. The Feynman diagram for heavy neutrino decay.

REFERENCES

1. M. Fritschi *et al.*, Phys. Lett. 173B (1986) 485
2. R. Albela *et al.*, Phys. Lett. 146B (1984) 431
3. H. Albrecht *et al.*, Phys. Lett. 163B (1985) 404
4. Sun Hong Rhie, Ph.D. thesis and to be published.
5. G. 't Hooft and M. Veltman, Nucl. Phys. B153 (1979) 365
6. E. Ma and A. Pramudita, Phys. Rev. D22 (1980) 214
7. A. Axelrod, Nucl. Phys. B209 (1982) 349; V. Ganapathi et al., Phys. Rev. D27 (1983) 579
8. G. Mann and T. Riemann, Annal. Physik. 40 (1983) 334

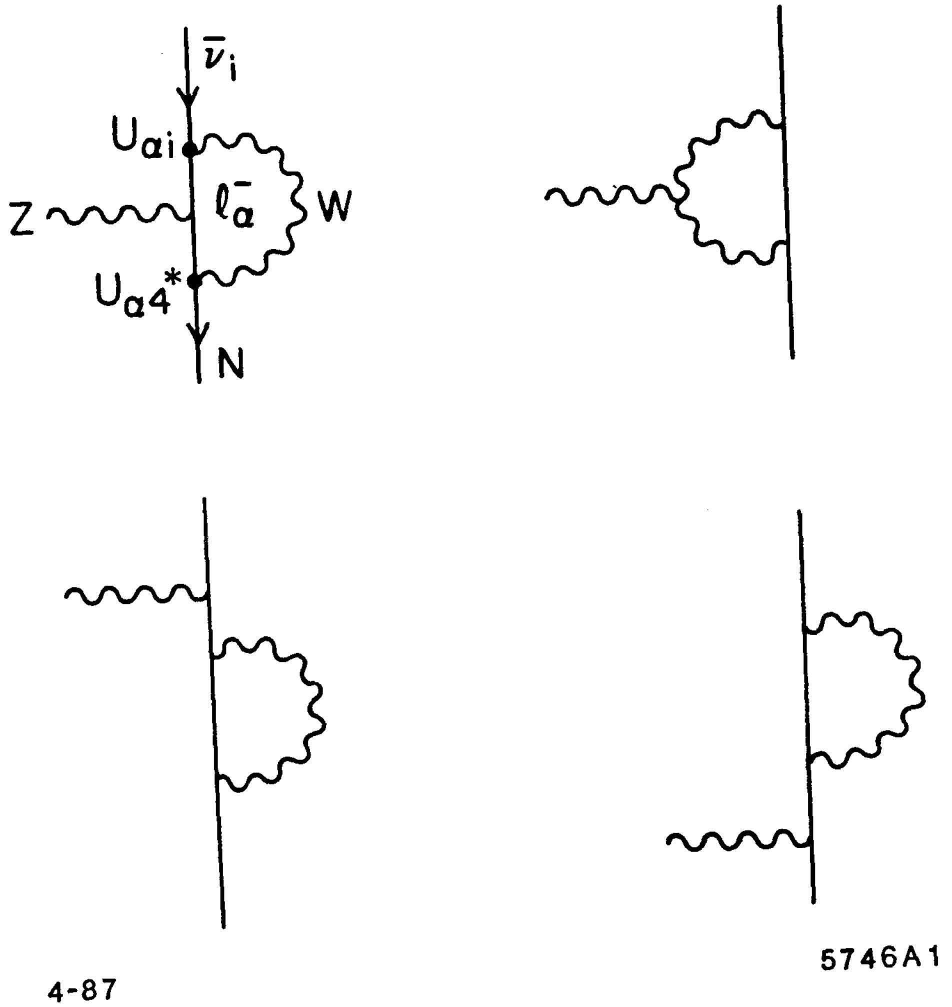

FIG. 1

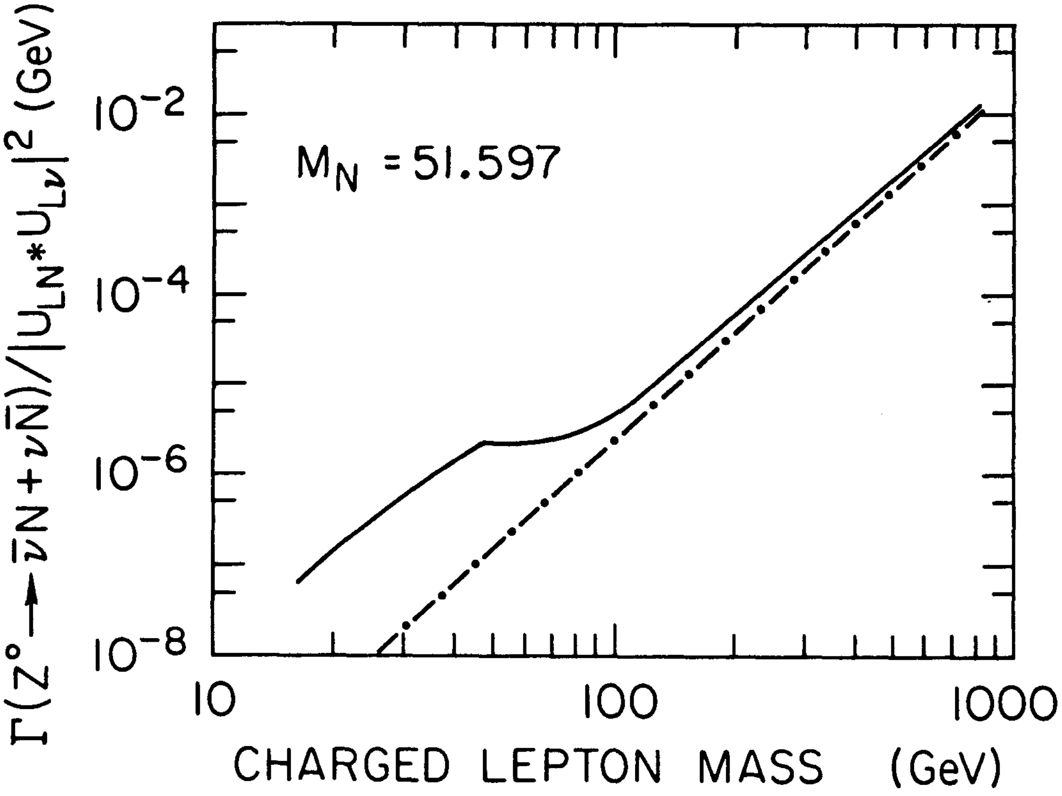

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FIG. 2

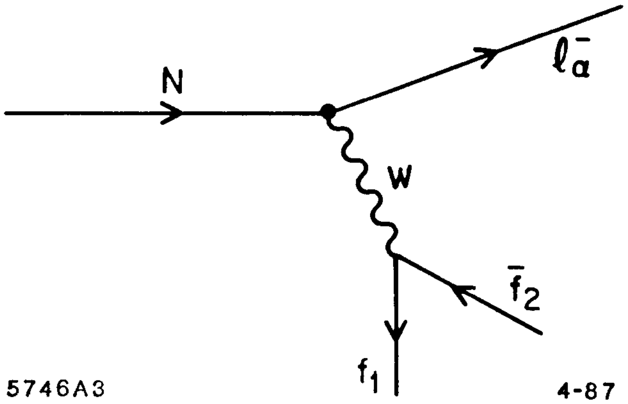

FIG. 3