Helicity effects in neutral heavy lepton decays

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The search for the existence of neutral heavy leptons may provide valuable information regarding plausible extensions to the standard model. In order to accurately study the decay of neutral heavy leptons, it is essential to include the helicity effects which arise from their non-zero mass. In this paper, we specifically examine the effects of helicity on the leptonic and semi-leptonic decays of neutral heavy leptons. [S0556-2821(98)06211-0]

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INTRODUCTION

The search for the existence of neutral heavy leptons continues to be a prominent area of research in high energy physics. Neutral heavy leptons are plausible extensions to the standard model [1]. In several models, the neutral heavy leptons are heavy isosinglets that interact and decay by mixing with their lighter neutrino counterparts. Several studies have been devoted to neutral heavy leptons, and approximate lifetimes and cross sections have already been calculated [2–4]. However, the effects of polarization on the decay of the neutral heavy leptons so far have not been included in full detail [5]. This paper specifically addresses the helicity effects of neutral heavy leptons on the angular distribution of the decay products.

NEUTRAL HEAVY LEPTONS

Neutral heavy leptons (L^0) may exist as isosinglets that decay via W or Z boson exchange and mixing. Because of the non-zero mass, however, it is no longer possible to assume complete right or left handed helicities. If we take, for example, the decay $K^+ \rightarrow l^+ + L^0$, the helicity of the L^0 will vary as a function of its mass [1]. This example is illustrated in Figs. 1 and 2. A complete picture of the neutral heavy lepton decay must therefore include helicity effects.

In this paper, we address the effects of helicity on the decay of neutral heavy leptons. Specifically, we examine closely the effects of polarization on leptonic and semi-leptonic decays. The calculation provides a description of the distribution of the decay products of the neutral heavy lepton. This calculation is applicable to previous and ongoing L^0 searches in many experiments, including CCFR [6], NuTeV [7], CHARM [8], NOMAD, and CHORUS.

In particular, the NuTeV experiment is using an instrumented decay channel specifically designed to search for neutral heavy leptons. The neutral heavy leptons result via decays from pions, kaons, and charm mesons made by 800 GeV protons interacting with a beryllium target. A fraction of the neutral heavy leptons, in turn, would decay within the decay channel, which consists of 40 meters of instrumented helium bags located after 1.4 km of shielding. This decay channel allows NuTeV to be particularly sensitive to low-mass neutral heavy leptons decaying into $\mu\mu\nu$, $\mu e\nu$, $ee\nu$, $\pi\mu$, and πe. It is thus crucial that all effects due to non-zero mass, including helicity, be studied in order to correctly model and detect these exotic particles.

MATRIX ELEMENTS

The matrix element of the neutral heavy lepton decays can be derived from the appropriate set of diagrams. Let us take the simplest of the reactions, whereby the L^0 decays mixing via the W boson into two distinct charged leptons (l_i and $\overline{l}_j$) and a neutrino (ν_j). The matrix element is written as

$$M = \frac{G_F}{\sqrt{2}}[\overline{u_{L^0}}\gamma^\mu(1-\gamma^5)u_{l_i}][\overline{v_{l_j}}\gamma_\mu(1-\gamma^5)u_{\nu_j}]. \qquad (1)$$

Squaring the matrix element, we find

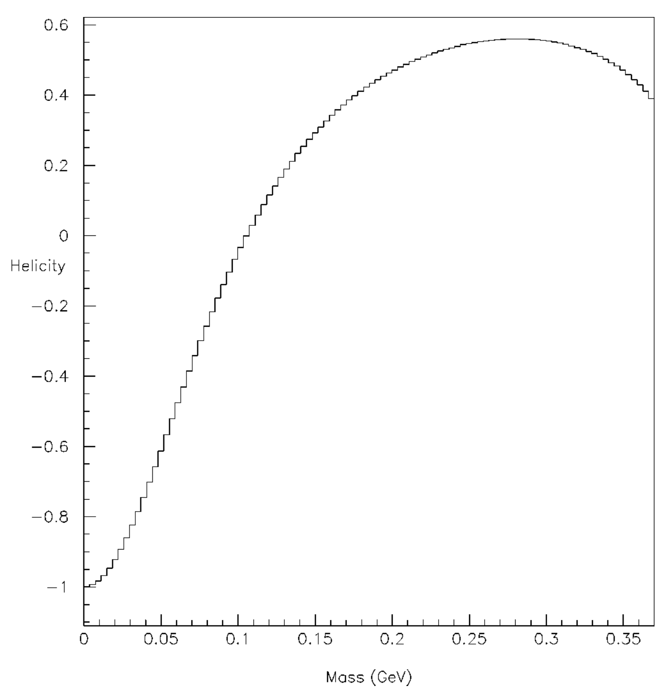

FIG. 1. Polarization of L^0 vs mass in decay $K^+ \rightarrow \mu^+ + L^0$.

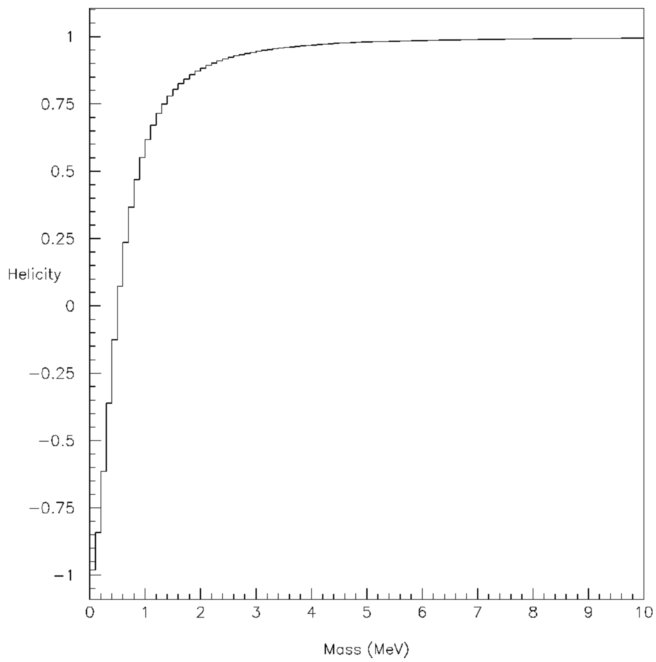

FIG. 2. Polarization of L^0 vs mass in decay $K^+ \to e^+ + L^0$.

$$|M|^2 = \frac{1}{2} G_F^2 Q_1 Q_2 \tag{2}$$

$$Q_1 = \mathrm{Tr}[u_{L^0}\overline{u}_{L^0}\gamma_\mu(1-\gamma^5)u_{l_i}\overline{u}_{l_i}\gamma_\sigma(1-\gamma^5)] \tag{3}$$

$$Q_2 = \mathrm{Tr}[v_{l_j}\overline{v}_{l_j}\gamma^\mu(1-\gamma^5)u_{\nu_j}\overline{u}_{\nu_j}\gamma^\sigma(1-\gamma^5)]. \tag{4}$$

Concentrating on the $u_{L^0}\overline{u}_{L^0}$ term in Q_1, we note that we can write this as

$$u_{L^0}\overline{u}_{L^0} = \frac{1}{2}(\not{p}_{L^0} + m_{L^0})(1+\gamma^5\not{s}). \tag{5}$$

Here $\not{s}$ are the 4-polarizations of the neutral heavy lepton. It is possible to show that

$$u_{L^0}\overline{u}_{L^0}\gamma^\mu(1-\gamma^5) = \frac{1}{2}[(\not{p}_{L^0} - m_{L^0}\not{s})(\gamma^\mu(1-\gamma^5)) + (m_{L^0} - \not{p}_{L^0}\not{s})(\gamma^\mu(1-\gamma^5))]. \tag{6}$$

Thus we can make the simple substitution $p_{L^0} \to p_{L^0} - m_{L^0}s$ as we go from unpolarized solutions to polarized solutions, as long as the matrix element does not explicitly depend on the mass of the L^0, which for our cases it does not. In the case $L^0 \to l_i \overline{l}_j \nu_j$, our polarized matrix element is given by

$$|M_{unpol}|^2 = 2G_F^2(p_{L^0}\cdot p_{l_j})(p_{l_i}\cdot p_{\nu_j}) \tag{7}$$

$$\downarrow$$

$$|M_{pol}|^2 = 2G_F^2((p_{L^0} - m_{L^0}s)\cdot(p_{l_j}))(p_{l_i}\cdot p_{\nu_j}). \tag{8}$$

This substitution technique works in all the other cases considered in this paper.

Next we list the matrix element from $L^0 \to$ meson + lepton, with the polarization effects included:

$$|M_{unpol}|^2 = 2G_F^2 f_M^2[2(p_{L^0}\cdot p_M)(p_M\cdot p_l) - p_M^2(p_{L^0}\cdot p_l)] \tag{9}$$

$$\downarrow$$

$$|M_{pol}|^2 = 2G_F^2 f_M^2[2((p_{L^0} - m_{L^0}s)\cdot p_M)(p_M\cdot p_l) - p_M^2((p_{L^0} - m_{L^0}s)\cdot p_l)]. \tag{10}$$

Lastly, we calculate the matrix elements from $L^0 \to l^+ l^- \nu_l$. In this case, we must also consider the contribution due to Z^0 decay:

$$|M|^2 = 16G_F^2[\sigma(p_1\cdot p_{l^+})(p_{l^-}\cdot p_{\nu_l}) + \beta(p_1\cdot p_{l^-})(p_{l^+}\cdot p_{\nu_l}) - \gamma m_l^2(p_1\cdot p_{\nu_l})]. \tag{11}$$

where

$$\sigma = 8\sin\theta_w^4 \tag{12}$$

$$\beta = 2(2+\cos 2\theta_w)^2 \tag{13}$$

$$\gamma = 4(2+\cos 2\theta_w)\sin\theta_w^2 \tag{14}$$

and

$$p_1 = p_{L^0} - m_{L^0}s. \tag{15}$$

This last matrix element was calculated using HIP [9], a MATHEMATICA program designed to solve Feynman diagrams. HIP was also used as a consistency check for the other matrix elements. With polarization effects now part of our calculations, we proceed to calculate the decay rates as a function of helicity.

DECAY RATES AND DIFFERENTIAL DISTRIBUTIONS

We use the matrix elements listed above to calculate the decay rates and distribution of the decay products. We begin with the decay of $L^0 \to$ meson + lepton, working in the rest frame of the neutral heavy lepton. If we let θ be the angle between polarization vector and the lepton, then the differential decay rate becomes

$$\frac{d\Gamma}{d\cos\theta} = \frac{G_F^2 f_M^2 m_{L^0}^3\sqrt{S}}{16\pi}\left[(1-\delta_l)^2 - \delta_M(1+\delta_l) - \frac{\sqrt{S}}{2}(1-\delta_l)\cos\theta\right]. \tag{16}$$

Here δ_M, δ_l, and S are defined as

$$\delta_M = \left(\frac{m_{Meson}}{m_{L^0}}\right)^2 \tag{17}$$

$$\delta_l = \left(\frac{m_{lepton}}{m_{L^0}}\right)^2 \tag{18}$$

$$S=1+\delta_M^2+\delta_l^2-2\,\delta_M-2\,\delta_l-2\,\delta_M\delta_l\,. \tag{19}$$

We can also calculate the differential decay width for $L^0\to l_i\overline{l}_j\nu_j$, where $i\neq j$. If we integrate over the appropriate variables, we find

$$\frac{d\Gamma}{dE_i dE_j d\cos\theta_i}=\frac{G_F^2}{128\pi^3}(m_{L^0}^2+m_j^2-m_i^2-2m_{L^0}E_j)\times(E_j+\sqrt{E_j^2-m_j^2}\cos\theta_j) \tag{20}$$

and for θ_j, we have

$$\frac{d\Gamma}{dE_i dE_j d\cos\theta_j}=\frac{G_F^2}{128\pi^3}(m_{L^0}^2+m_j^2-m_i^2-2m_{L^0}E_j)\times(E_j+\sqrt{E_j^2-m_j^2}\cos\theta_\nu\cos\theta_i) \tag{21}$$

where $\cos\theta_\nu$ is given as

$$\cos\theta_\nu=\frac{(m_{L^0}-E_i-E_j)^2-E_i^2+m_i^2-E_j^2+m_j^2}{2\sqrt{E_i^2-m_i^2}\sqrt{E_j^2-m_j^2}}. \tag{22}$$

(The i and j subscripts refer to the variables associated with the l_i and l_j leptons respectively.)

Lastly, we calculate the differential decay of $L^0\to l^+l^-\nu_l$. Letting θ_- and θ_+ be the angles of the lepton and anti-lepton respectively, we find

$$\frac{d\Gamma}{dE_+dE_-d\cos\theta_-}=\frac{G_F^2}{16\pi^3}[\sigma(E_-+p_-\cos\theta_-)+\beta(E_++p_+\cos\theta_-\cos\theta_\nu)-2\gamma m_l^2E_\nu(1+\cos\theta_\nu)] \tag{23}$$

and also

$$\frac{d\Gamma}{dE_+dE_-d\cos\theta_+}=\frac{G_F^2}{16\pi^3}[\sigma(E_-+p_-\cos\theta_+\cos\theta_\nu)+\beta(E_++p_+\cos\theta_+)-2\gamma m_l^2E_\nu(1+\cos\theta_\nu)] \tag{24}$$

where m_l is the mass of the lepton, and

$$p_\pm=\sqrt{E_\pm^2-m_l^2} \tag{25}$$

$$E_\nu=m_{L^0}-E_+-E_- \tag{26}$$

and σ, β, and γ are given by Eqs. (12)–(14).

Sample distributions for various decays and mass values are shown in Figs. 3 and 4. All distributions were created by randomly generating events with the appropriate matrix elements. Note that the $a+b\cos\theta$ behavior, as well as the mass dependence of the distributions, is clearly apparent.

As a result of the non-uniform angular distribution of the decay products of the L^0, there is also a non-negligible effect in the energy distribution. This distribution changes as a function of polarization. Figure 5 shows the energy distribution of the μ^- from the decay $L^0\to\mu^-e^+\nu_e$ for several helicities. The other decay modes show similar distributions. In addition, with the exception of decay processes where the two charged leptons are identical, there also exists an asymmetry between the charged particles that is dependent on the polarization of the neutral heavy lepton. An example of this asymmetry is shown in Fig. 6. Both the asymmetry, as well as the energy distribution of the decay products, could have significant effects in both event analysis and reconstruction of neutral heavy leptons.

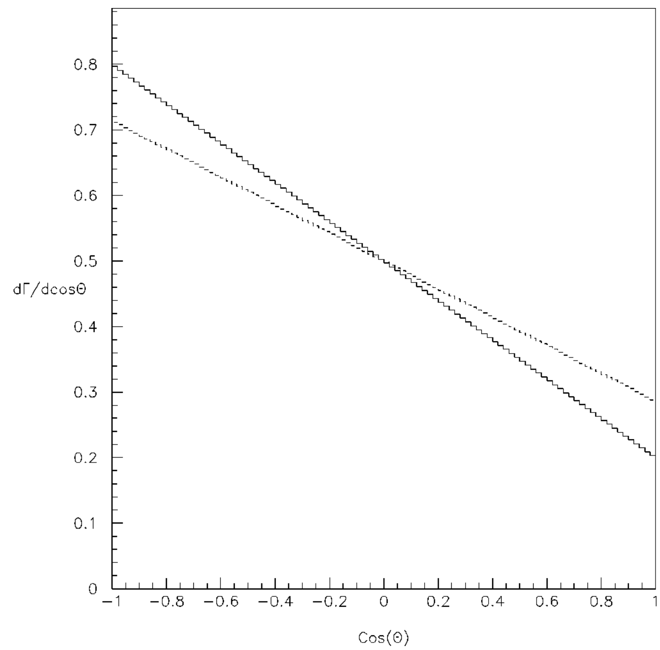

FIG. 3. Angular distribution of μ^- in fully polarized (helicity +1) decay of $L^0\to\mu^-e^+\nu_e$ for masses of 0.5 GeV (solid line) and 5 GeV (dashed line).

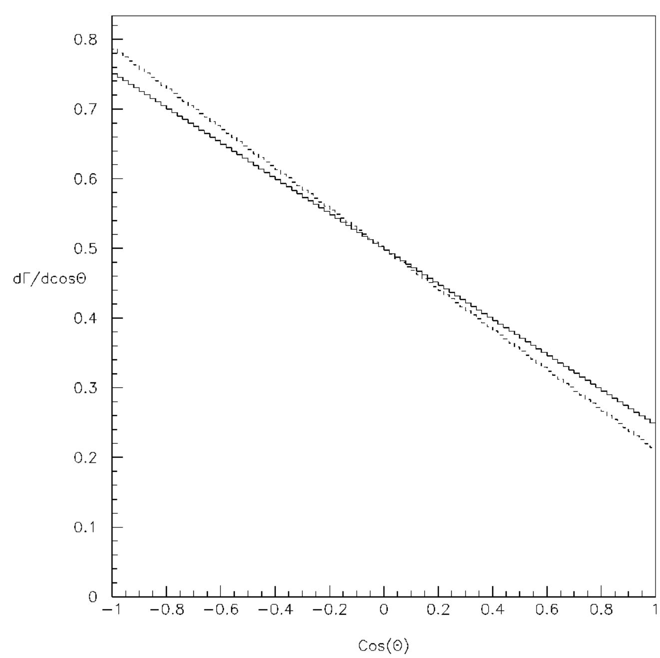

FIG. 4. Angular distribution of μ^- in fully polarized (helicity +1) decay of $L^0\to\mu^-\mu^+\nu_\mu$ for masses of 0.5 GeV (solid line) and 5 GeV (dashed line).

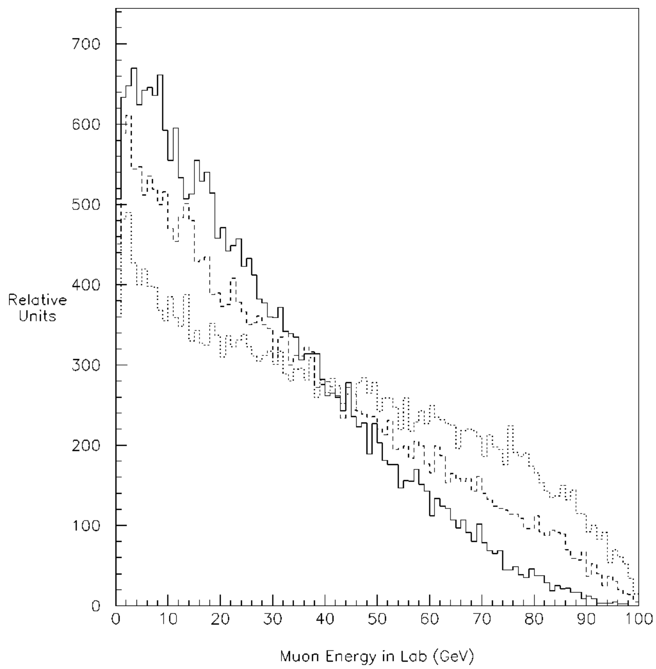

FIG. 5. Energy distribution of μ^- from $L^0 \rightarrow \mu^- e^+ \nu_e$ for helicity$+1$ (solid line), 0 (dashed line), and -1 (dotted line). The L^0 have a mass of 5 GeV/c^2 and energy of 100 GeV.

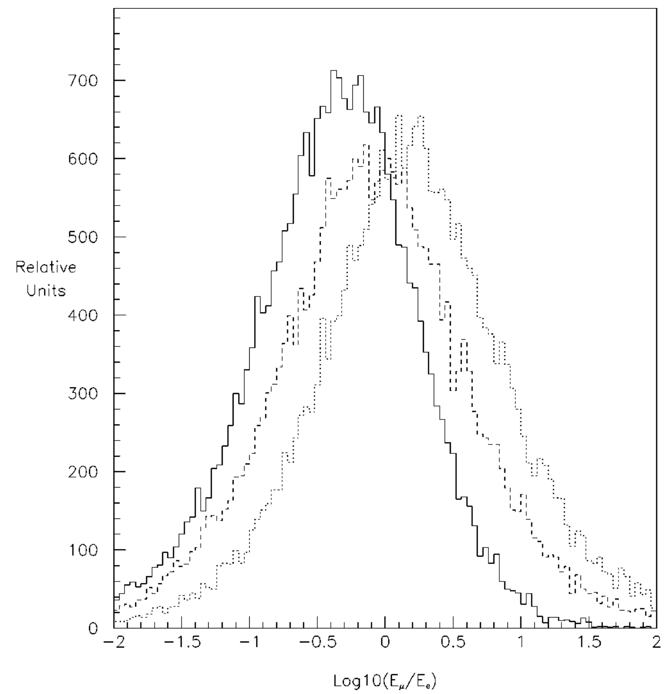

FIG. 6. Distribution for the $\log_{10}(E_{\mu^-}/E_{e^+})$ ratio in $L^0 \rightarrow \mu^- e^+ \nu_e$ decay for helicity $+1$ (solid line), 0 (dashed line) and -1 (dotted line). The L^0 have a mass of 5 GeV/c^2 and energy of 100 GeV.

CONCLUSION

We have calculated the helicity dependent distributions for the decay of neutral heavy leptons to mesons and/or leptons. Because of the non-zero mass of the neutral heavy leptons, polarization does affect both the angular and energy distribution of the decay products. These results are applicable to all neutral heavy lepton searches and, in particular, the ongoing NuTeV [7], NOMAD, CHORUS, and the previous CHARM [8] neutrino experiments.

[1] F. Boehm and P. Vogel, *Physics of Massive Neutrinos* (Cambridge University Press, Cambridge, England, 1992).

[2] M. Gronau, C.N. Leung, and J.L. Rosner, Phys. Rev. D **29**, 2539 (1984).

[3] R.E. Shrock, Phys. Rev. D **24**, 1232 (1981); **24**, 1275 (1981).

[4] T. Bolton, L. Johnson, and D. McKay, Phys. Rev. D **56**, 2970 (1997).

[5] L.M. Sehgal and P.M. Zerwas, Phys. Rev. D **16**, 2379 (1977).

[6] P. de Barbaro *et al.*, in *New and Exotic Phenomena '90: Proceedings*, edited by O. Fackler and J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1990), p. 37.

[7] J. Conrad, NuTeV DET019 (1994).

[8] C. Santoni *et al.*, *Tignes 1986, Proceedings, '86 Massive Neutrinos*, edited by O. Fackler and J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1986), pp. 229–240.

[9] A. Hsieh and E. Yehudai, SLAC PUB 5576 (1991).