HEAVY LEPTON MIXING

A muon storage ring offers ample opportunities to search for new phenomena in yet unexplored physical regions. One such opportunity is the ability to search for the existence of neutral heavy leptons. Several models describe heavy isosinglets that interact and decay by mixing with their lighter neutrino counterparts [1,7]. The high intensity neutrino beam created by the muon storage ring provides an ideal setting to search for neutral heavy leptons with a mass below the muon mass, 105.6 MeV/c^2.

It is postulated that neutral heavy leptons (L_0) could be produced from muon decay when one of the neutrinos mixes with its heavy, isosinglet partner. Neutral heavy leptons can be produced via one of two channels:

$$\mu^- \rightarrow L_0 + \overline{\nu}_e + e^- \tag{1}$$

$$\mu^- \rightarrow \nu_\mu + L_0 + e^- \tag{2}$$

The branching ratio for each of these reactions is given by:

$$BR(\mu \rightarrow L_0 \mu e) = |U_i|^2 (1 - 8x_m^2 + 8x_m^6 - x_m^8 + 12x_m^4 \ln x_m^2) \tag{3}$$

Here $x_m \equiv m_{L_0}/m_\mu$ and $|U_i|^2$ is the mixing constant between the specific type of neutrino and the neutral heavy lepton: $U_i \equiv \langle L_0|\nu_i\rangle$. Note that $|U_\mu|^2$ and $|U_e|^2$ need not be identical.

Once produced, a neutral heavy lepton of such low mass will either decay via $L_0 \rightarrow \nu\nu\nu$, $L_0 \rightarrow \nu ee$, or $L_0 \rightarrow \gamma\nu$. The most viable mode for detection is the two-electron channel. For this particular decay mode, the L_0 can decay either via charged current or charged and neutral current interactions. The branching ratio for this decay process has been previously calculated [3]. Since the decay width is proportional to U_j^2, the number of L_0's detectable is proportional to $U_i^2 * U_j^2$ in the limit where the distance from the source to the detector is short compared to the lifetime of the L_0.

Using the above model, one can estimate the number of neutral heavy leptons produced at the muon storage ring which later decay within a given detector. The number of detected neutral heavy leptons is given by the equation below:

$$N_{L_0} = N_\nu * BR(\mu \rightarrow L_0 \nu e) * \epsilon * e^{-L/\gamma c\tau} * BR(L_0 \rightarrow detectable) * (1 - e^{-\delta l/\gamma c\tau}) \tag{4}$$

Here N_ν is the number of neutrinos produced from muon decay, $BR(\mu \rightarrow L_0 \nu e)$ is the branching ratio of muons decaying into neutral heavy leptons versus ordinary muon decay, L is the distance from the beamline to the detector, δl is the length of the detector, ϵ is the combined detector and geometric efficiency, τ is the L_0 lifetime, and $BR(L_0 \rightarrow detectable)$ is the branching ratio for the neutral heavy lepton decaying via a detectable channel (presumably $L_0 \rightarrow \nu ee$).

In testing the sensitivity to L_0 production at the muon storage ring, we make a few underlying assumptions. We assume that the storage ring utilizes a pure, unpolarized muon beam with straight sections such that 25 percent of the muons will decay to neutrinos pointing towards the detector. We assume that the fiducial volume is 3 meters in diameter and 30 meters in length, and that the detector has sufficient tracking resolution to detect the e^+e^- vertex from the L_0 decay. We assume for now that the background is negligible. These parameters correspond to the fiducial volume of the decay channel used for the L_0 search at E815 (NuTeV) [4,5].

The sensitivity of the detector has been calculated for a number of different muon energies and beam intensities. Figure 1 shows limits on the L_0-ν_μ mixing as a function of L_0 mass. One achieves the best limits from using relatively low energy/high intensity muon beams. This is a major improvement over previous neutral heavy lepton searches, where limits do not reach below $6.0 * 10^{-6}$ in the low mass region [6,7].

The single event sensitivity quoted here depends greatly on having minimal background levels in the signal region. Part of this can be achieved by kinematic cuts which discriminate against neutrino interactions in the detector material. However, it will probably be necessary to reduce the amount of material in the fiducial region greatly compared to NuTeV. We estimate that even if the decay region is composed only of helium gas, the number of neutrino interactions will approach a few thousand. The ideal detector, therefore, would consist of a long vacuum or quasi-vacuum pipe with appropriate segmentation for tracking. The decay pipe could be used in conjunction with larger neutrino detectors adapted for the muon storage ring.

The muon storage ring may prove to be an ideal location to continue the search for neutral heavy leptons. The high intensity neutrino beam allows for a neutral heavy lepton search to be sensitive to the $10 - 100$ MeV/c^2 mass range. In addition, such a neutral heavy lepton program could easily interface with a neutrino detector which uses the same neutrino beam. It is also clear, however, that a neutral heavy lepton search would receive the most benefit at lower muon energies, and thus would yield best results at the earlier stages of the muon storage ring program.

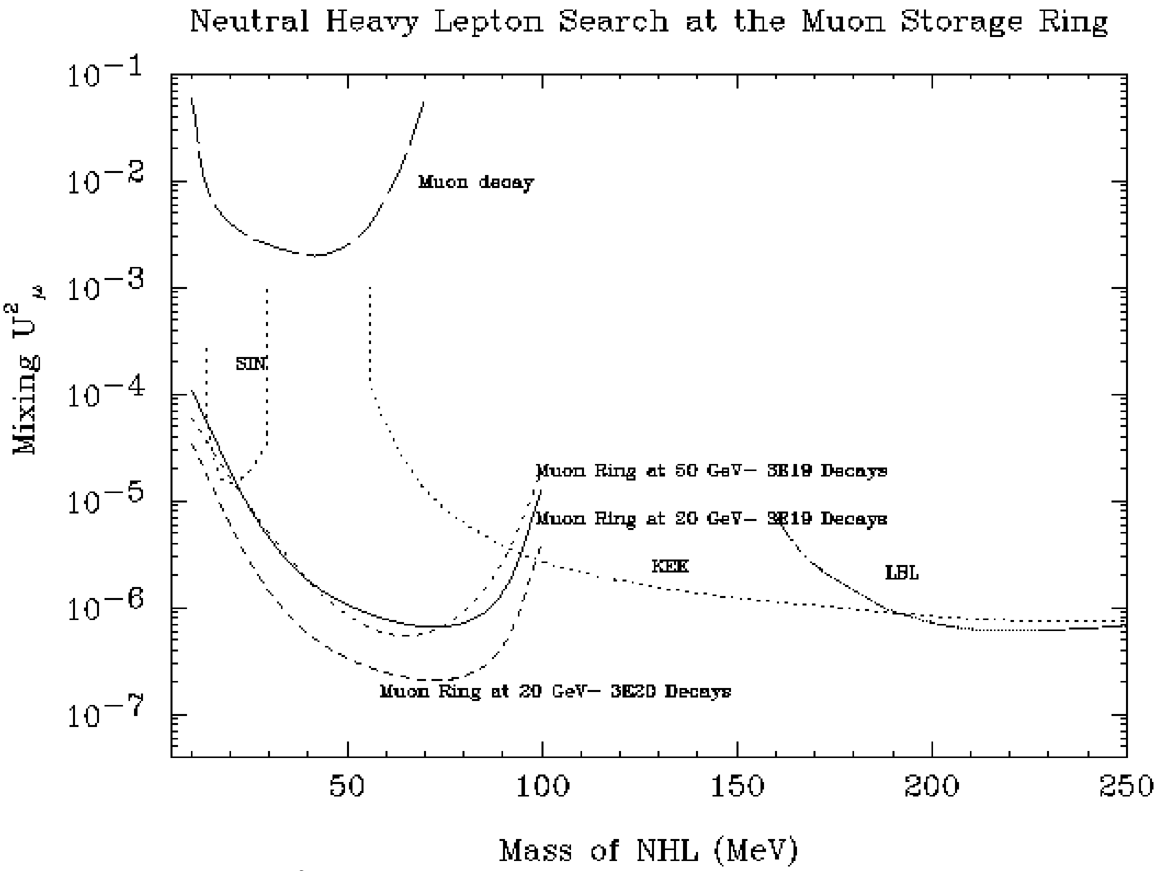

FIG. 1. Limits on $|U_{\mu L}|^2$ as a function of L_0 mass for one year of running. The curves show sensitivities for 20 GeV and 50 GeV muon energies. Sensitivities assume no background events in signal region.

NEUTRINO MAGNETIC MOMENTS

Although neutrino oscillation searches focus on the mass differences between neutrino eigenstates, neutrinos can possess other observable properties. If discovered, the magnitude of the neutrino magnetic moment (NMM) would provide the Standard Model neutrino eigenstate mass through a direct relationship (Equation **??**). A measurement of the NMM would have great importance for the development of stellar models, and knowledge of the neutrino mass would have even greater impact in the field of cosmology. Even failing the goal of a measurement, an improved limit could constrain several Standard Model extensions. As shall be seen, a NMM search can run parasitically as the front–end to a typical long baseline detector.

Despite their lack of charge, a neutrino can possess a non-zero magnetic moment that can arise through loop diagrams. In the Standard Model, extended only insofar as the presence of a right–handed neutrino, or such that left–handed neutrinos are allowed to have mass, the expected [8] neutrino magnetic moment magnitude is given by

$$\mu_\nu \simeq 3 \times 10^{-19}\ \mu_{Bohr} \cdot \left(\frac{m_\nu}{1\ \mathrm{eV}}\right), \tag{5}$$

where μ_{Bohr} is the Bohr magneton. Several extensions to the SM would result in a much larger NMM; supersymmeteric models can produce $10^{-14}\mu_{Bohr}$ to $10^{-12}\mu_{Bohr}$ [9] and calculations that invoke large extra dimensions easily yield $10^{-11}\mu_{Bohr}$ or larger [10].

Relative to the SM expectation, the excluded values of NMM are not at all stringent, being seven to nine orders of magnitude larger. The current limits on neutrino magnetic moment from laboratory experiments are $\mu_\nu \leq 1.5$ to $1.8\times10^{-10}\mu_{Bohr}$ for electron neutrinos [11] [12] and $\mu_\nu \leq 7.4\times10^{-10}\mu_{Bohr}$ for muon neutrinos [13]. Astrophysical limits are stronger: the slow rate of plasmon decay in horizontal branch stars [14] implies $\mu_\nu \lesssim 10^{-11}\mu_{Bohr}$, while the neutrino energy loss rate from supernova 1987a [15] yields $\mu_\nu \lesssim 10^{-12}\mu_{Bohr}$. Note, however, that several assumptions are implicit to the astrophysics limits, including the core temperature of the stars; if stellar models omit important processes, these limits may be overestimated. Also, the supernova limit applies only to Dirac neutrinos and not to the Majorana case.

Existing search schemes possess a weakness that sharply limits their ultimate sensitivity: the formulae for the hypothesized effect are quadratic in μ_ν but linear in terms of the experimenter–controlled parameters. In contrast, the following scheme is quadratic in terms of the product of the NMM and a magnetic field strength, μ_ν·B; hence it has a chance of exceeding the limits from current experiments and possibly the limits from astrophysics calculations.

The energy E of a neutrino in a magnetic field B gains a new term μ_ν·B. Consider a B field along the x-axis, and a neutrino with momentum and helicity along the z-axis at $t = 0$. The eigenstates of the neutrino are projections along the x-axis, and the state of the neutrino is expressed as:

$$|{\uparrow}\rangle = \frac{e^{-i(E+\mu_\nu B)t}}{\sqrt{2}}\,|{\leftarrow}\rangle + \frac{e^{-i(E-\mu_\nu B)t}}{\sqrt{2}}\,|{\rightarrow}\rangle\,. \tag{6}$$

As the neutrino propagates, the relative phase of the two components changes, corresponding to a rotation to a sterile state in the case of a Dirac neutrino or to an antineutrino in the Majorana case. At a far detector, the signal would be a deficit in the number of neutrinos detected with the B field in place compared the number detected without the B field.

In this phase rotation scheme, the energy splitting occurs as the neutrino passes through a field gradient and experiences a force $F = \nabla(\mu_\nu \cdot \mathrm{B})$. To preserve the energy difference, so that the phase difference can continue to accumulate on the way to the far detector, the field must be turned off instead of allowing the neutrino to experience the reverse gradient as it exits the field region.

There are thus two basic requirements for the magnetic field:

1) The magnetic field must oscillate such that the neutrino experiences only one sign of the gradient. This study assumes that the neutrino bunch length is small compared to the oscillation length. If this assumption is not true, the effects discussed here will be diluted but the basic conclusions will still apply.

2) The magnetic field must be as strong as possible.

We have explored the possibility [16] of using two existing technologies for the B field: resonant cavities and kicker magnets. In both cases the maximum magnetic field is too small to yield improved magnetic moment limits given realistic equipment.

As an alternative, we envision many superconducting wires comprising a large current sheet, not unlike one wall of existing (~ 2 T) collider detector solenoids. Consider a neutrino passing through an infinite current sheet from left to right. While the neutrino is on the left, the current ramps up from zero to maximum, resulting in a B field that is homogeneous in space. As the neutrino passes through the sheet, it experiences a magnetic gradient of 2·B. As the neutrino continues to the right, the current drops again to zero, bringing B to zero also. Placing sheets in series linearly increases the rate of phase rotation.

The formula for the number of events lost to sterile states may be expressed very simply as:

$$N_{lost} = N * \sin^2(\mu_\nu \mathrm{B} t) \tag{7}$$

We note that, in contrast to an oscillation disappearence signal, this effect is independant of energy. Figure 2 compares this result to the expected statistical fluctuations in the number of CC events (N) observed in a 50 kton [17] far detector. We see that for ten 1 T field gradients and 10^{19} muon decays we expect a greater–than–ten–sigma sensitivity to a NMM of $10^{-11}\mu_{Bohr}$. With only three 1 T gradients, the limit drops below two sigma. The sensitivity can be increased very strongly by increasing the field strength and having many gradient stages, and also by increasing the number of events in the far detector by increasing the number of muon decays or the detector mass. Because the detector distance deterimines both t and N in Eqn. 7, the "significance" in the figure is linear in terms of distance.

To conclude, we have discussed a novel neutrino magnetic moment search technique that uses oscillating magnetic fields at the source of a long baseline detector's neutrino beam. This is the only technique we know of that is quadratic in both μ_ν and another parameter, and thus has the potential for arbitrary sensitivity as we improve our ability to create oscillating magnetic field gradients.

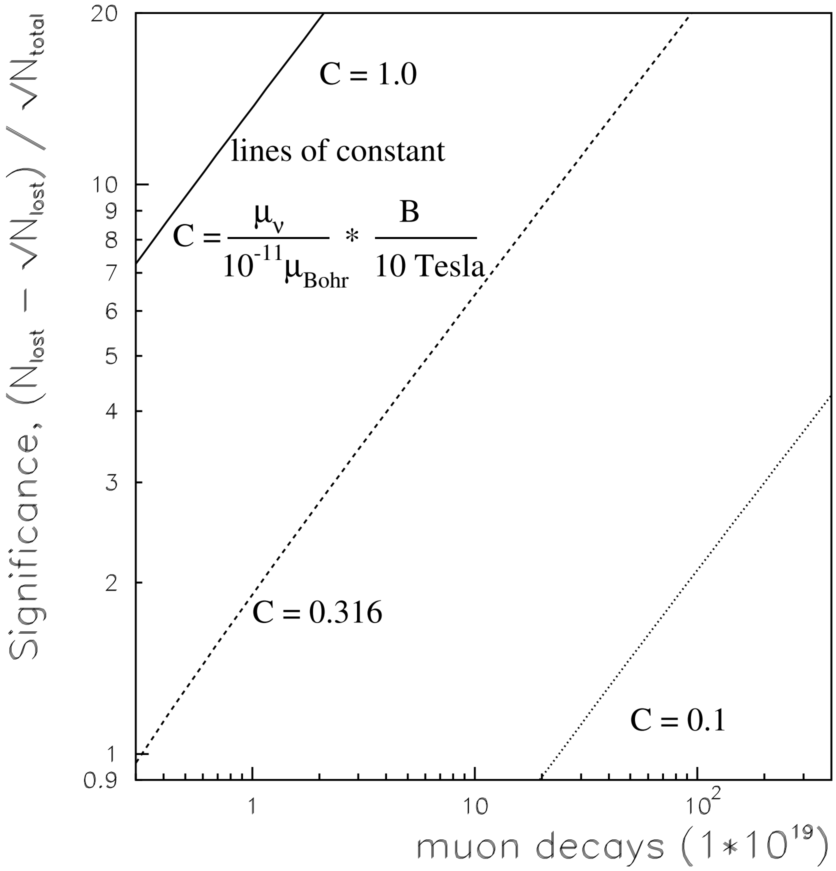

FIG. 2. Significance for several scenarios.

ANOMOLOUS LEPTON PRODUCTION

The neutrino beam from a muon storage ring would consist of a virtually pure combination of $\bar{\nu}_e$ and ν_μ (or charge-conjugate). Also, at the source of the neutrino beam, the $\bar{\nu}_e$ and ν_μ will not have had time to oscillate into other flavors: For a 20 GeV muon storage ring with a 700 m straight section, and neutrino oscillations with $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2, the oscillation probability is $\approx 5 \times 10^{-9}$. Furthermore, the neutrino flux is highest at the source. Thus, an experiment at the neutrino source could be highly sensitive to exotic processes resulting in production of e^-, μ^+, or τ of either charge. While such a search is interesting in its own right, it is also useful to rule out exotic contributions to long-baseline neutrino oscillation signals.

These exotic processes would probably have a flat or rising dependence on the neutrino energy E_ν. In contrast, a neutrino oscillation would have a $1/E_\nu^2$ dependence. Also, if the distance L of the experiment changes, the rate of exotic events would decrease with the flux as $1/L^2$. In contrast, the neutrino oscillation probability would increase as L^2 (for L small compared to the oscillation period), and so the rate of oscillated events would be independent of L. Thus, one could distinguish between exotic processes and the beginning of a neutrino oscillation.

Anomalous lepton production could occur if muons decay to neutrino flavors other than those in the usual decay $\mu \to e\bar{\nu}_e\nu_\mu$, and the anomalous neutrinos then interact in the target. Alternatively, they could be produced if a $\bar{\nu}_e$ or ν_μ interacts with the target via an exotic process.

The only direct experimental limit on exotic $\mu \to e\bar{\nu}_x\nu_y$ decays is $BR(\mu \to e\bar{\nu}_\mu\nu_e) < 1.3\%$ [18]. Indirect limits are also very weak. The contribution of non- $V - A$ interactions to the muon decay rate has been limited to 8% [18]. Also, the total muon decay rate is one of the main measurements used to constrain electroweak parameters [18]. To first order,

$$\frac{1}{\tau_\mu} = \frac{G_F m_\mu^5}{192\pi^3}. \tag{8}$$

Assuming the standard model, G_F is determined to 1 part in 10^5 from muon lifetime measurements. If there are exotic contributions to the muon lifetime, the measured value of G_F would be shifted from the true value. Since

$$m_W \propto G_F^{-1/2}, \tag{9}$$

the 0.1% uncertainty on m_W corresponds to a 0.4% shift in the muon lifetime. Finally, the CKM matrix element V_{ud} is determined from the rate of nuclear β-decays relative to the muon lifetime. The assumption of unitarity on the CKM matrix gives us the following constraint on the first row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ud}|^2 = 1. \tag{10}$$

The experimental determination is [18]:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ud}|^2 = 0.991 \pm 0.005. \tag{11}$$

The uncertainty on this constraint corresponds to a 0.5% shift in the muon lifetime. Additional contributions to the muon decay rate would lead to a downward shift in the determined value of $|V_{ud}|^2$ from the true value. We conclude that exotic decay modes of the muon with branching ratios totaling 0.5% are possible without contradicting current measurements or tests of the standard model.

As a concrete example of such an exotic process we consider R-parity-violating supersymmetric models. These models lead to lepton-number-violating vertices with couplings λ, and muon decay processes such as $\mu \to e\bar{\nu_\tau}\nu_\tau$ as shown in Fig. 1. The matrix element for these decays turns out to have the same form as for the standard W-exchange. The current constraints on the couplings λ are reviewed in Ref. [19]. These constraints allow a branching ratio of 0.4% for the process in Fig. 3.

Similar processes are allowed for anomalous lepton production as shown for example in Fig. 3. Estimates for allowed rates are in progress [20]. These diagrams involve the λ' couplings. Currently, the best limit on one of these couplings, λ'_{231}, is from ν_μ deep-inelastic scattering, so existing neutrino data is already providing constraints! The search for these types of effects at the muon storage ring could be input into a decision on whether to build a muon-proton collider where they could be studied in more detail.

As a start on estimating the capabilities of an experiment at the neutrino source, we consider the detector concept illustrated in Fig. 4. This concept consists of a repeating sequence of 1.5 mm-thick Tungsten sheets with Silicon tracking, separated by 4 mm. Tungsten, being dense, provides a high target mass while being thin enough for a produced τ to have a high probability of hitting the Silicon. The impact parameter of the τ decay products is typically 90 microns with a broad distribution, so we would like a hit resolution of 5 microns or better. Although there is a lot of multiple scattering in the tungsten, the short extrapolation distance provides for a good impact parameter resolution on the τ decay products. This configuration has been optimized for a 50 GeV muon beam. For lower energy beams, the planes should be spaced more closely, and the Tungsten thickness perhaps reduced. Studies of detectors with passive target mass and tracking with emulsion sheets [21] suggest that we can expect τ reconstruction efficiencies as high as 30%.

We would propose placing such a detector in a magnetic field, and measuring the momentum of muons and hadrons should be straightforward. However, each Tungsten sheet is 0.4 radiations lengths thick, and while we should obtain good energy resolution for electromagnetic showers, determining the electron charge will be difficult. We estimate it would take roughly a 4 Tesla field transverse to the beam direction to have a good chance of measuring the charge of a 50 GeV electron. Even then, detailed studies are needed to determine if this can be done reliably.

A total mass of 6 tons of Tungsten corresponds to 200 m^2 of Silicon tracking. For 5×10^{20} muon decays at 50 GeV, we expect a total of 35 billion neutrino interactions. Obviously there is much potential for sensitivity to very rare exotic processes, but detailed simulations and studies of possible Silicon tracking technologies are needed to quantify this.

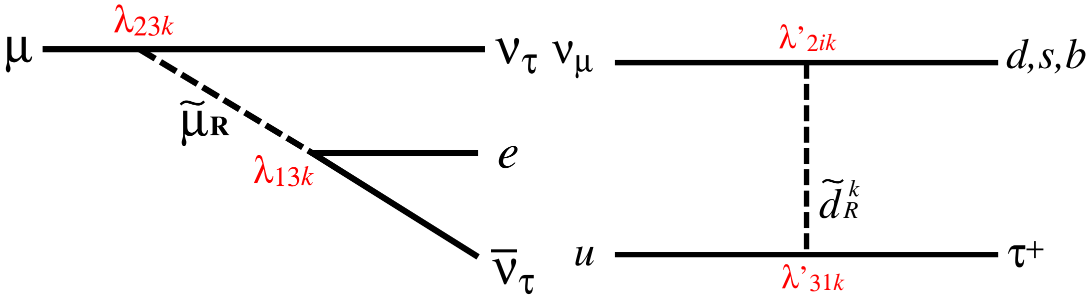

FIG. 3. Example of exotic muon decay in R-parity-violating SUSY (Left), and an example of an exotic neutrino interaction in R-parity-violating SUSY (Right).

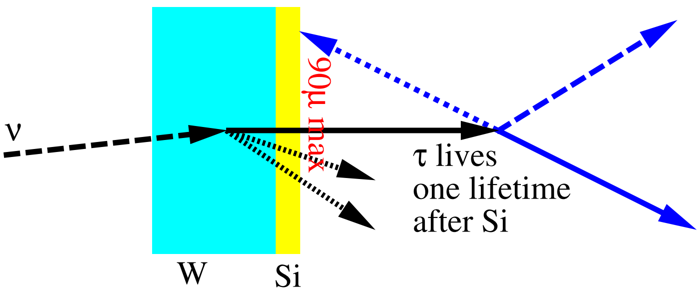

FIG. 4. One plane of a detector for τ production.

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