

$\mu + N \rightarrow \tau + N$ at a Muon or Neutrino Factory

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Abstract

The experimental discovery of large $\nu_\mu - \nu_\tau$ mixing indicates that analogous mixing in the charged lepton sector could be substantial. We consider the possibility that if a high intensity muon beam, perhaps at the early stages of a muon or neutrino factory, strikes a nuclear target, then conversion of some of the muons into tau leptons could occur (similar to the conversion of muons to electrons at MECO). Using current experimental limits on rare tau decays to bound the size of the relevant operators, we find that a 50 GeV muon beam, with 10^{20} muons on target per year, could yield as many as 10^7 $\mu + N \rightarrow \tau + N$ events per year. Backgrounds could be substantial, and we comment on the possibility of detection of this process.

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In the past decade, the biggest surprise in our understanding of flavor physics has been the discovery of large mixing [1] in the neutrino sector. This large mixing may come from diagonalization of the neutrino mass matrix, the charged lepton mass matrix, or both. It is quite possible that searches for charged lepton flavor violation will be critical in determining the physics of flavor violation.

The most promising such search is the MECO experiment [2], in which a high intensity, low energy muon beam strikes a nuclear target. The muons are captured, and decay essentially at rest. The conversion $\mu + N \rightarrow e + N$ will then yield a distinctive 105 MeV electron. The experiment promises to achieve the extraordinary sensitivity of a part in 10^{17} , and in many models beyond the standard model, a positive signal would be expected.

Observations of atmospheric neutrinos indicate that mixing between the muon and tau neutrinos is maximal. This gives strong motivation for considering transitions between the muon and the tau. Of course, the analogous process to MECO, $\tau + N \rightarrow \mu + N$, is impractical due to the short lifetime of the τ . However, the inverse process, $\mu + N \rightarrow \tau + N$ might be possible. Unlike MECO, this can't occur for muons at rest, but in a higher energy muon beam, one can look for such events. Such high energy and high intensity muon beams are expected [3] at neutrino factories (or early stages of muon factories), in which intensities of 10^{20} muons per year and beam energies up to 50 GeV have been proposed. In this note, we examine whether the $\mu + N \rightarrow \tau + N$ process is feasible at such a neutrino factory.

The existence of the process $\mu + N \rightarrow \tau + N$ immediately implies that there will be muon and tau number violating rare τ decays, such as $\tau \rightarrow \mu\pi, \tau \rightarrow \mu\pi\pi, \tau \rightarrow \mu\rho$, etc. The non-observation (as yet) of these decays implies an upper bound on $\mu + N \rightarrow \tau + N$. We first examine the upper bound on the size of the various operators.

The relevant operators are of the form $(\bar{\mu} \Gamma \tau)(\bar{q}^\alpha \Gamma q^\beta)$, where Γ contains various combinations of Dirac gamma matrices. A detailed analysis of all 48 possible operators, where the

q 's are any combination of the six quarks and the Γ consists of $(1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5)$ was carried out recently by Black, et al. [4]. They determined the experimental lower bound on Λ for each process, where Λ is defined by the considering the relevant operator to be

$$\frac{4\pi}{\Lambda^2}(\bar{\mu} \Gamma \tau)(\bar{q}^\alpha \Gamma q^\beta). \quad (1)$$

For simplicity, we will consider valence quarks only, and will assume that the operators are isospin invariant, so that the operators involving u -quarks and d -quarks are the same magnitude. Relaxing this assumption will only strengthen our results. Black, et al. find that the lower bound on Λ for $\Gamma = (1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5)$ is (2.6, 12, 12, 11) TeV, which come from $\tau \rightarrow \mu\pi^+\pi^-$, $\tau \rightarrow \mu\pi^0$, $\tau \rightarrow \mu\rho$ and $\tau \rightarrow \mu\pi^0$, respectively. Since the bound on the scalar operator is the weakest, we will assume that the operator is scalar, and is thus

$$\frac{4\pi}{\Lambda^2}(\bar{\mu} \tau)(\bar{q} q), \quad (2)$$

where q is u or d and Λ is greater than 2.6 TeV. No experiment can currently exclude such a possibility. When our results are presented, we will briefly comment on the effects of choosing one of the other three operators.

With this operator, we can calculate the cross section for $\mu + q \rightarrow \tau + q$, and we find that

$$\sigma(\mu + q \rightarrow \tau + q) = \left(\frac{\pi s}{3\Lambda^4}\right) \left(1 - \frac{m_\tau^2}{s}\right)^2 \left(1 + \frac{m_\tau^2}{2s}\right). \quad (3)$$

Folding in the parton distribution functions, we plot the cross section for $\mu + N \rightarrow \tau + N$, where N is a nucleon, in Figure 1, assuming that the lower bound on Λ is saturated. For the expected beam energy of 50 GeV, the cross section is 0.55 fb.

With this cross section, we can determine the mean free path. If ρ is the density of the target (in g/cm³), the mean free path is

$$\lambda = \frac{1}{\rho} \left(\frac{1 \text{ fb}}{\sigma}\right) (1.6 \times 10^{13}) \text{ meters}. \quad (4)$$

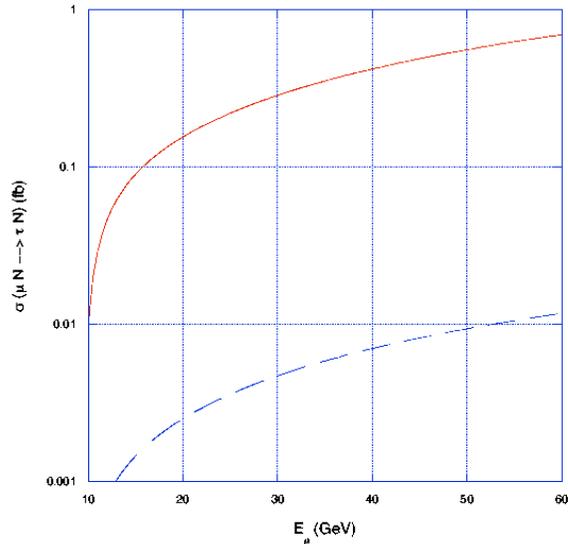


Figure 1: The cross section for the scattering $\mu N \rightarrow \tau N$ in units of fb as a function of muon energy (GeV) in Lab frame. The solid (dashed) line represents the cross section assuming a scalar (vector) interaction.

For a 50 GeV muon beam, there is little ionization loss over a meter of target, and thus there is a probability of approximately $3 \times 10^{-14}\rho$ of interacting in a meter of target. With 10^{20} muons on target is a year, this gives $3 \times 10^6\rho$ events per year per meter of target.

We have assumed that the interaction is scalar. If it is vector, there is a factor of 8 increase in the square of the matrix element (in the massless limit), however the lower bound on Λ is 12 TeV instead of 2.6 TeV, leading to a lower event rate. This is also plotted in Figure 1. Nonetheless, even here there could be well over 100,000 events per year. Using pseudoscalar or axial vector operators will give similar results. But for the scalar case, and a fairly dense target, the event rate could exceed 10^7 events per year.

Although this seems to be a huge event rate, the backgrounds could be severe. Note, however that the cross section for tau pair production through Bethe – Heitler production off iron nuclei [5] is much smaller than a femtobarn, and the p_T distributions are much softer, so tau pair production will not be a problematic background. The major difficulty is identifying

a clear signature. A typical τ energy, for a 50 GeV incident beam energy, will be tens of GeV, and thus its decay distance would be a couple of millimeters. One can imagine alternating target and scintillator, but many τ 's will be missed. The only places in which τ 's have been detected are the clean environment of electron-positron colliders, the Tevatron, where the signature is large missing transverse energy, and DONUT [6]. The latter used lead and emulsions as the target and detection media, and it isn't clear whether the enormous intensity of the incident muon beam would blacken the emulsion (this would depend on the beam size and whether the emulsion is cycled in and out). This possibility should be investigated. What are the specific decay modes that might be observable? The leptonic decays will clearly be swamped by backgrounds. The $\pi\nu$ decay mode will lead to a monochromatic pion, but unless a τ track can be observed, the backgrounds for single pions in the intense muon beam will also be very large. One could look at rarer decays, such as the three charged pion (or even five charged pion) decays, coming at the end of a very short track. Clearly, detection of this process will not be easy, but the event rate is high enough that a clever scheme might be able to pick out a signal.

Are there specific models which predict such a large rate for $\mu + N \rightarrow \tau + N$? The Standard Model, with massive neutrinos, will have mixing between the μ and the τ , but this mixing is of the order of m_ν^2/m_W^2 , and is thus negligible. However, there are a wide variety of extensions of the Standard Model, including models with very heavy neutrinos, horizontal symmetries, left-right symmetry, supersymmetry, extended gauge and Higgs models, etc., and many of these do predict such mixing to occur at a substantially higher rate. The effects of $\mu - \tau$ mixing can be parametrized by operators of the form of Eq. (1). As noted earlier, the biggest rates for $\mu + N \rightarrow \tau + N$ occur if the operator is scalar, as in Eq. (2) (since the experimental limits on the operator are weaker), and thus models with flavor-changing scalar exchanges are most promising. For example, in R-parity violating supersymmetry [7], the

superpotential can be written in the form $\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD_k$. If the underlying theory giving rise to this superpotential gives a hierarchical structure for λ , so that λ_{123} is large, and a non-hierarchical structure for λ' , then the operator of Eq. (2) can be generated via scalar neutrino exchange. If the couplings are of order unity, and the scalar neutrino mass is of the order of a TeV, then the operator will be as large as allowed by bounds on $\tau \rightarrow \mu\pi\pi$ and the rate for $\mu + N \rightarrow \tau + N$ will be as large as discussed in the previous paragraph. Alternatively, supersymmetric models at large $\tan\beta$ can have very large flavor-changing Higgs couplings [8], and that can also lead to similarly large muon to tau conversion. Thus, we see that plausible extensions of the Standard Model exist in which $\tau \rightarrow \mu\pi^+\pi^-$ is near its current limit,

The early stages of a neutrino or muon factory will involve a high intensity muon beam with energies up to 50 GeV. In this Brief Report, we have proposed that such a facility may be able to substantially improve bounds on $\mu - \tau$ mixing, or discover such mixing, by looking for muon conversion in nuclei to tau leptons. The event rate could be high, although backgrounds will be challenging. In view of the large mixing in the neutrino sector, this may be a promising place to search for new flavor physics.

After this work was completed, we became aware of a very interesting paper by Gninenko, Kirsanov, Krasnikov and Matveev [9]. They also considered the process $\mu + N \rightarrow \tau + N$ at a neutrino factory. Instead of considering the vertex involving valence quarks, as we did, they considered the four-fermi interaction $(\bar{\mu}\tau)(\bar{u}c)$, involving production of a charmed quark. This has a substantial advantage over our vertex, which is flavor diagonal, because there are no experimental constraints on the size of this interaction (since τ 's can't decay into a charmed meson plus a muon). As a result, they had a much higher event rate, and could consider the muonic decay of the τ . They performed a simulation of the signature at the NOMAD detector. What is new in our work? We considered the flavor diagonal vertex, which is more tightly constrained by experimental bounds. Our belief is that it is very unlikely for the

four-fermi interaction to be purely off-diagonal in the mass eigenstate basis, and thus the existence of the vertex considered by Gninenko et al. will generally imply the existence of the vertex that we have considered. In that sense, this work is complementary to theirs. Clearly, there is sufficient interest in the possibility of mu-tau conversion in nuclei that all experimental possibilities should be considered.

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