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NEUTRINO FACTORIES - PHYSICS POTENTIALS

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Neutrino Factories– Physics Potentials

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Abstract. The recent results from Super-Kamiokande atmospheric and solar neutrino observations opens a new era in neutrino physics and has sparked a considerable interest in the physics possibilities with a Neutrino Factory based on the muon storage ring. We present physics opportunities at a Neutrino Factory, and prospects of Neutrino oscillation experiments. Using the precisely known flavor composition of the beam, one could envision an extensive program to measure the neutrino oscillation mixing matrix, including possible CP violating effects. These and Neutrino Interaction Rates for examples of a Neutrino Factory at BNL (and FNAL) with detectors at Gran Sasso, SLAC and Sudan are also presented.

INTRODUCTION

A muon storage ring based Neutrino Source (Neutrino Factory) beside providing a first phase of a muon collider facility, it would generate more intense and well collimated neutrino beams than currently available. The BNL- AGS or some other proton driver would provide an intense proton beam that hits a target, produces pions that decay into muons. The muons must be cooled, accelerated and injected into a storage ring with a long straight section where they decay. The decays occurring in the straight sections of the ring would generate neutrino beams that could be directed to detectors located thousands of kilometers away, allowing studies of neutrino oscillations with precisions not currently accessible [4].

The composition and spectra of an intense neutrino beam from a muon storage ring depends on momentum, polarization and charge of the stored muons, through the decays $\mu^- \to e^-\nu_\mu\bar{\nu}_e$ or $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$.

The neutrino fluxes from the proposed muon-based beams would be higher than ever previously achieved with a much better-understood flavor composition. In ad-

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dition, since the neutrino beams from these sources would be secondary beams from high energy muon decays, they would be extremely well collimated. Distances between production and detection could, therefore span the globe. Using the precisely known flavor composition of the beam, one could envision an extensive program to measure the neutrino oscillation mixing matrix, including possible CP violating effects.

NEUTRINO OSCILLATION

With only two massive neutrinos, with mass difference $\Delta m^2 = m_2^2 - m_1^2$, mass eigenstates ν_1 and ν_2 with mixing angle θ, the flavor eigenstates become:

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}. \qquad (1)$$

The probability that a neutrino of flavor ν_a and energy E appears as flavor ν_b after traversing distance L in vacuum is

$$P(\nu_a \to \nu_b) = \sin^2\left(1.27\Delta m^2[\mathrm{eV}^2]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)\sin^2 2\theta. \qquad (2)$$

Since the atmospheric neutrino data involves GeV muon neutrinos with distance scales of the Earth's diameter, this suggests Δm^2 of order 10^{-3} $(\mathrm{eV})^2$ for $\sin^2 2\theta \approx 1$. The solar neutrino data involves MeV electron neutrinos and distance scales of the radius of the Earth's orbit, suggesting Δm^2 of order 10^{-10} $(\mathrm{eV})^2$ with $\sin^2 2\theta \approx 1$ for vacuum oscillations [15]. The LSND result involves 30-MeV muon antineutrino and a distance scale of 30 m, suggesting Δm^2 of order 1 $(\mathrm{eV})^2$; large mixing angles are excluded by reactor data [16] , thus, $\sin^2 2\theta$ can only be of order 10^{-2} in this case. Obviously, four different massive neutrinos are required to accommodate all three results, given their disparate scales of Δm^2. The Standard Model presently includes only three neutrinos with standard electroweak couplings and $m_\nu < m_Z/2$, so a "sterile" neutrino is required if all the data are correct citesterile. Even discarding the LSND result, three massive neutrinos are required with a corresponding 3×3 mixing matrix, e.g.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \qquad (3)$$

a MNS matrix [18], where $c_{12} = \cos\theta_{12}$, *etc.*., In the three massive neutrino model, the neutrino oscillation probabilities of interest depends on six measurable parameters: three mixing angles (θ_{12}, θ_{13}, θ_{23}); a phase δ related to CP violation as indicated in eq. (3); and two differences of the squares of the neutrino masses (Δm_{12}^2 and Δm_{23}^2 for instance). The interpretation of the solar and atmospheric neutrino data in terms of the three-neutrino oscillation hypothesis suggests $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$, with Δm^2_{12} and Δm^2_{23} being responsible for the transitions and/or oscillations of the solar and atmospheric neutrinos, respectively.

The description of the atmospheric neutrino data requires $\Delta m^2_{23} \approx (2-6) \times 10^{-3}$ eV^2 and large mixing angle θ_{23}: $\sin^2 2\theta_{23} \approx (0.9-1.0)$. For $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$ and with Δm^2_{23} in the above range, the non-observation of oscillations of the reactor electron antineutrinos in the CHOOZ experiment [19] implies a limit on the angle θ_{13}: $\sin^2 \theta_{13} < 0.11$. Given these constraints, the transitions/oscillations of the solar neutrinos in the three-neutrino mixing scheme under discussion depend largely on the remaining two parameters: Δm^2_{12} and $\sin^2 2\theta_{12}$.

Further, the presence of matter may modify the oscillations of electron neutrinos because of their charged-current interaction (MSW effect [20]). In particular, the oscillations can be resonantly enhanced by the matter effects even when the oscillation probabilities are small in vacuum. This leads to additional interpretations of the solar neutrino data in which Δm^2_{12} can be of order 10^{-5} (eV)^2 [21]. In effect at the present time , there are four viable interpretations of the solar neutrino data:

1) Vacuum oscillation (VO) solution with $\Delta m^2_{12} \approx (0.5-5.0) \times 10^{-10}$ eV^2 and $\sin^2 2\theta_{12} \approx (0.7-1.0)$,

2) Low MSW solution corresponding to $\Delta m^2_{12} \approx (0.5-2.0) \times 10^{-7}$ eV^2 and $\sin^2 2\theta_{12} \approx (0.9-1.0)$,

3) Small mixing angle (SMA) MSW solution with $\Delta m^2_{12} \approx (4.0-9.0) \times 10^{-6}$ eV^2 and $\sin^2 2\theta_{12} \approx (0.001-0.01)$,

4) Large mixing angle (LMA) MSW solution, $\Delta m^2_{12} \approx (0.2-2.0) \times 10^{-4}$ eV^2 and $\sin^2 \theta_{12} \approx (0.65-0.96)$.

With four interpretations of the solar neutrino data, and the two interpretations of the LSND data as either right or wrong, there are a total of eight scenarios for explanations of the data. The experimental challenge is to reduce these to a single scenario, and to make accurate measurements of the parameters of that scenario.

Thus, with the available experimental guidelines as to the parameters of neutrino masses and mixings, one can begin to plan for more extensive studies namely, with neutrino beams derived from the decay of muons in a storage ring. Both μ^- and μ^+ can be stored in the ring, but only one sign would be used at a time. For example if μ^- are stored, their decay

$$\mu^- \to e^- \nu_\mu \overline{\nu}_e, \tag{4}$$

leads to beams with nearly equal numbers of ν_μ and $\overline{\nu}_e$ with spectra that are well known.

At the detectors, the neutrino and the antineutrino may or may not have changed their flavor, leading to the appearance of a different flavor or the disappearance of the initial flavor, respectively. When detected by a charged-current interaction, there are 6 classes of signatures in a three-neutrino model:

1) $\nu_\mu \to \nu_e \to e^-$ (appearance);

2) $\nu_\mu \to \nu_\mu \to \mu^-$ (disappearance);

3) $\nu_\mu \to \nu_\tau \to \tau^-$ (appearance);

4) $\overline{\nu}_e \to \overline{\nu}_e \to e^+$ (disappearance);

5) $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$ (appearance);

6) $\overline{\nu}_e \to \overline{\nu}_\tau \to \tau^+$ (appearance).

For operation with positive muons, a similar list of processes may be written. The 5th process where a muon of different sign from the parent muon appears, has a very unique possibilities at a neutrino factory based on muon storage rings. Since they are the only sources of intense high energy electron (anti)neutrino beams. The τ appearance (cases 3 and 6) are practical only for neutrino beams with 10's of GeV energy.

Experiments carried out at a neutrino factory within the next decade can add compelling new information to our understanding of neutrino oscillations, if the number of useful muon decays exceeds 10^{19} per year, and energy is $\gtrsim 20$ GeV.

It is anticipated that by the time a muon storage ring would be built the two angles (θ_{23} and θ_{12}), and the magnitudes of two mass squared differences (Δm^2_{23} and Δm^2_{12}) would be known, from the solar and atmospheric neutrino measurements (which would have been verified by long baseline and reactor experiments), for example, MINOS and KamLAND. The remaining pieces of the puzzle would be θ_{13}, the CP-violating phase δ and the signs of the Δm^2_{ij}. Moreover, the indicated long-baseline experiments will not be sensitive to the matter effects in neutrino oscillations because the distances between the sources and detectors are not sufficiently large. Verifying the existence of matter effects in neutrino oscillations by observing directly the modification of the neutrino oscillation probabilities by these effects, would also be fundamental and interesting.

The third mixing angle θ_{13} can be measured in several channels at a neutrino factory The detector must be far to avoid background but not too far (< 1000 km) so that the effects of Δm^2_{12} remain negligible and thus δ can formally be set to zero. Fig. 1 shows the achievable sensitivity to the yet-unknown value of θ_{13},

and illustrates sensitivity reach in the $(\sin^2\theta_{13}, \Delta m^2_{23})$ plane for a 10 kton detector and a neutrino beam from 2×10^{20} decays of 20 GeV muons in a storage ring at distance 732 km. The appearance process $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$, shown by the lines on the left, has much greater sensitivity than the disappearance process $\nu_\mu \to \nu_\mu \to \mu^-$, shown by the lines on the right. The interior of the box is the approximate region allowed by Super-Kamiokande data [15].

CP VIOLATION

The three-neutrino scenario [23] can lead to CP violation in for example

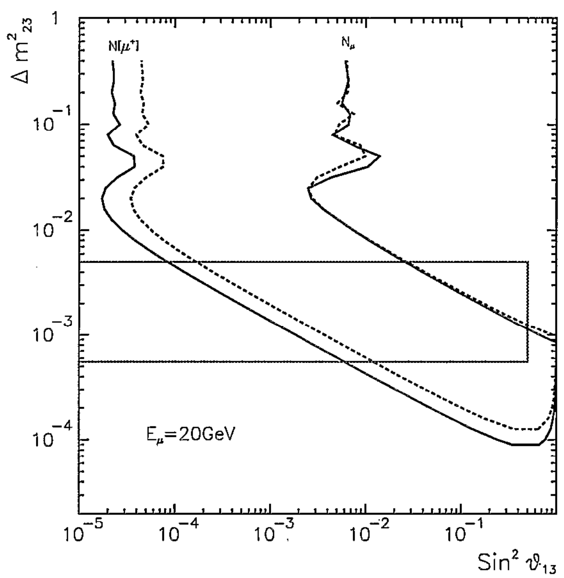

FIGURE 1. Sensitivity reach in the $(\sin^2\theta_{13}, \Delta m^2_{23})$ plane.

$$A_{\mathrm{CP}} = \frac{P(\nu_e \to \nu_\mu) - P(\overline{\nu}_e \to \overline{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\overline{\nu}_e \to \overline{\nu}_\mu)}, \tag{5}$$

or time-reversal violation

$$A_{\mathrm{T}} = \frac{P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)}{P(\nu_e \to \nu_\mu) + P(\nu_\mu \to \nu_e)}. \tag{6}$$

The asymmetry (5) can be measured using wrong-sign muons and the two charges of the muon beam. However, the genuine CP violating contribution to (5) due to a non-vanishing phase δ competes with terms related to matter effects, *i.e.*, to the different rates of evolution for ν_e and $\overline{\nu}_e$ between source and detector. The relative strength of the matter-induced asymmetry increases quadratically with distance, and dilutes the signal of CP violation in a far detector.

If the solution to solar neutrino problem involves, large mixing angles and matter enhancement (LMA MSW, $\sin^2 2\theta_{12} \approx \sin^2 2\theta_{23} \approx 1$), then there is a possibility of measuring the CP violating asymmetry (5), with expression

$$|A_{\mathrm{CP}}| \approx \left| \frac{2\sin\delta}{\sin 2\theta_{13}} \sin\left(\frac{1.27\Delta m^2_{12} L}{E}\right)\right|, \tag{7}$$

provided the detector is located sufficiently far and high statistics ($> 10^{21}$ muons per year) are available. For all the other solar neutrino solutions A_{CP} is extremely small, being suppressed by a factor of either $\sin^2 2\theta_{12}$ or Δm^2_{12}.

The asymmetry (6) is not sensitive to matter effects, but relies on distinguishing the process $\nu_\mu \to \nu_e \to e^-$ from $\overline{\nu}_e \to \overline{\nu}_e \to e^+$. In the detector, it will be very difficult to distinguish electrons from positrons but the relative ν_μ and $\overline{\nu}_e$ fluxes can be varied by varying the polarization of the muons in the storage ring [24].

If future experiments confirm the interpretation of the LSND data that there exist more than three light neutrinos, then use of the neutrino factory flavor-rich beams would be even more crucial, because the parameter space for CP/T violating effects would be considerably enlarged and could be explored in experiments with such beams [25].

PRECISION PHYSICS

Muon storage ring based neutrino beams would bring about new neutrino oscillation measurements, and a new era for high-precision neutrino scattering experiments [26]. For example, with a detector located 30 m from a 150 m straight section of a 50-GeV, 10^{21}-μ/yr muon storage ring, the event rate is 40 million events per kilogram per year over a 10 cm radius. Oscillation-related measurements may be interpreted precision measurements of the total neutrino and antineutrino cross sections, as well as of the beam divergence. As precision probes of nuclear and nucleon structure, the neutrinos may be used to provide additional information to that obtained with charged lepton beams, in related studies. It is known that, neutrino scattering allows a clean separation of the valence and sea quark distributions, and use of a polarized target permits characterization of the spin dependence of these distributions. Thus, near detectors are the natural successor to nucleon structure measurements presently underway at HERA, HERMES, Jefferson Lab, RHIC and elsewhere. For example, scattering of the four neutrino types ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$ off electrons could lead to measurements of the Weinberg angle ten times better than known at present.

Note that, a high-flux multi-GeV neutrino beam is a charm factory, in which a ν_μ beam leads to c quarks that are tagged by a final-state μ^- ($\nu_\mu d \to \mu^- c$), while $\overline{\nu}_\mu$ beam leads only to tagged $\overline{c}$ quarks. For example, for the above described beam parameters, there would be 10^7 leptonic tagged charm decays in only 40 kg-years (not kton-years!), permitting measurements of V_{cd} to fraction of a percent, and perhaps even direct observation of $D^0 - \overline{D}^0$ mixing.

EVENT RATES – POTENTIALS

The number of neutrino interactions per unit mass of a detector at distance L from a muon storage ring operating at energy E_μ scales as

$$N_{\text{events}} \propto N_\mu \, E_\mu^3 \, L^{-2} \tag{8}$$

for the example of a proton source with 1.5 MW power, in one year (10^7 s) of operation, there would be about 4×10^{20} muons per year decaying in the storage ring. Assuming the fraction of the ring pointing to a given detector to be about

TABLE 1. Neutrino Interaction Rates at a Neutrino Factory.

		Source at Detector at L (km)	BNL G. Sasso 6528	BNL SLAC 4139	BNL Soudan 1712	FNAL G. Sasso 7332	FNAL SLAC 2899	FNAL Soudan 732
Case		Mode						
1)	μ^+	$\nu_e \to \nu_\mu$	90	160	190	63	180	200
		$\nu_e \to \nu_e$	1400	3600	16000	1100	8000	1.2×10^5
			(2.4σ)	(2.7σ)	(1.5σ)	(1.9σ)	(2.0σ)	(0.6σ)
		$\overline{\nu}_\mu \to \overline{\nu}_\mu$	890	2200	9300	700	4800	7.0×10^4
2)	μ^+	$\nu_e \to \nu_\mu$	5×10^{-2}	0.86	1.5	3×10^{-5}	1.3	1.6
		$\nu_e \to \nu_e$	1500	3800	16000	1200	8200	1.2×10^5
		$\overline{\nu}_\mu \to \overline{\nu}_\mu$	890	2200	9400	700	4800	7.0×10^4
3)	μ^+	$\nu_e \to \nu_\tau$	31	60	70	20	67	73
		$\nu_e \to \nu_e$	1400	3700	1.6×10^4	1100	8000	1.2×10^5
			(2.4σ)	(2.7σ)	(1.5σ)	(1.9σ)	(2.0σ)	(0.6σ)
		$\overline{\nu}_\mu \to \overline{\nu}_\mu$	890	2200	9400	700	4800	7.0×10^4
4)	μ^-	$\nu_\mu \to nu_\tau$	450	570	650	410	620	680
		$\nu_\mu \to \nu_\mu$	760	3100	1.7×10^4	490	8000	1.4×10^5
			(35σ)	(23σ)	(12σ)	(40σ)	(16σ)	(4.6σ)
		$\overline{\nu}_e \to \overline{\nu}_e$	770	1900	8100	600	4100	6.1×10^4

0.25 then the number of decays pointing to the given detector will be approximately 10^{20}. It may be noted that the number of events with the 1.5 MW neutrino factory, in a detector at the same 730 km, is approximately 100 times that in the proposed CERN - Gran Sasso experiment (NGS) [9], and about 40 times the maximum event rate that MINOS [10] can expect. Upgrading the proton driver to 4 MW, the factors become about 300 and 100 for Gran Sasso and Soudan, respectively.

Table 1, gives charged current neutrino interaction rates (per kiloton-year) as a function of baseline length L for an $E_\mu = 50$ GeV muon storage ring in which there are 1×10^{20} unpolarized muon decays per year within a neutrino beam-forming straight section [14]. The rates are listed for oscillations:

1) $\nu_e \to \nu_\mu$: $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2/c^4 & $\sin^2 2\theta = 0.1$,

2) $\nu_e \to \nu_\mu$: $\Delta m^2 = 1 \times 10^{-4}$ eV^2/c^4 & $\sin^2 2\theta = 1$,

3) $\nu_e \to \nu_\tau$: $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2/c^4 & $\sin^2 2\theta = 0.1$,

4) $\nu_\mu \to \nu_\tau$: $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2/c^4 & $\sin^2 2\theta = 1$.

Table 1, also gives the rates for the unoscillated neutrino interactions, the corresponding statistical significance of the disappearance signal (numbers in parenthesis), and the rates for the antineutrino interactions.

If future experiments confirm the interpretation of the LSND data that there exist more than three light neutrinos, then use of the neutrino factory flavor-rich beams would be even more crucial, because the parameter space for CP/T violating effects would be considerably enlarged and could be explored in experiments with such beams [25].

SUMMARY

A Muon storage ring based neutrino factory has a strong physics case, but require additional feasibility studies. The recent more ambitious ideas for utilizing high intensity muon sources are being explored. Indeed, if very high intensities, $\sim 10^{21} \frac{\nu}{year}$, are attained and nature has been kind in her neutrino mass and mixing parameters, one could envision a complete exploration of the 3×3 neutrino mixing matrix and even the detection of CP violation in the oscillation phenomena. [2] - [29].

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