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Physics Opportunities at the Front End of an AGS-based Neutrino Factory

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Abstract

We give a brief overview of possible physics opportunities that could be available during a staged construction of a future AGS-based neutrino factory. The proton driver required in the first stage of such a facility would produce intense beams of kaons and muons suitable for rare decay experiments. Studies of muon to electron conversion in matter or the branching ratio for rare K decays, such as $K\rightarrow \pi \nu \nu$, may be suitable experiments at this stage. In the second stage the cooled medium-energy muon beam could be used for high sensitivity searches for an electric dipole moment of the muon. An improved high-sensitivity g-2 experiment could be performed during the third stage.

1. Introduction

The goal of a neutrino factory (NF) program is to accelerate muons to high energy and store them in a ring with long straight sections, in order to produce intense, well-characterized beams of neutrinos from muon decays. These neutrinos would then be used primarily for high rate oscillation experiments at a distant detector. In addition, specialized detectors near the storage ring could be used for high rate studies of neutrino interactions. Detailed studies have previously been completed of the neutrino physics opportunities at a NF [1]. In addition, studies have been done of the neutrino physics opportunities from a "superbeam", taken directly from the proton driver at the facility [2].

During the construction of a NF a number of particle beam resources would become available, which could, in principle, be used for other non-neutrino physics purposes. One possible scheme for staging the construction of an AGS-based NF project[1] is given in Table 1.

Table 1 Possible neutrino factory project phases

Phase 1	High power proton driver & target	0-24 GeV/c
Phase 2	Front end through cooling	200 MeV/c μ
Phase 3	Complete linac	2.5 GeV/c μ
Phase 4	Complete RLA & storage ring	20 GeV/c μ

In this report we give a brief overview of some important physics topics that could be addressed in the first three phases of the project. A previous look at physics possibilities in the context of a muon collider was made at a workshop [3] in 1997. A comprehensive review of stopping muon physics that could be done in conjunction with the CERN NF design [4] has recently been completed. The physics potential from using a new proton driver at FNAL was also examined at a recent workshop [5].

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[1] We use the parameters for the Muon Collaboration Feasibility Study 2 neutrino factory design in this report.

2. Phase 1 Opportunities

The first phase of the NF would involve the construction of a high power proton driver and a target station. A proton driver with a beam power of 1-4 MW and a target system that can handle this power level opens the door to the study of many physics topics. Table 2 lists some properties of the 1 MW configuration of the proton driver.

Table 2 Proton driver parameters

<p>	24	GeV/c
σ_p	0.12	GeV/c
σ_x	1.5	mm
σ_t	3	ns
Np / bunch	1.7×10^{13}	
N_{bunch}	6	
time between bunches	20	ms
f_{rep}	2.5	Hz

This proton beam has a total intensity of $2.5\ 10^{14}$ p/s and a complex time structure. There is an overall 400 ms cycle time. Inside this there are 6 very intense bursts of protons lasting for ~10 ns and separated from each other by 20 ms. This time structure is unsuitable for some of the interesting physics topics discussed below. In order to accommodate them the driver would have to be designed with the flexibility to change the pulse structure, or an additional accumulator ring would have to be provided to match the beam structure to the experiment's requirements.

This type of facility would have capabilities comparable to a kaon factory and could address a number of compelling physics topics [6]. The very high beam fluxes would be particularly helpful in searches for rare processes, which point to physics beyond the standard model. Table 3 gives a partial list of some interesting muon physics topics that could be addressed with such a facility. Pursuing this type of physics would require the construction of a high-quality muon beam line off the target area.

Table 3 Muon physics topics using the proton driver

muon lifetime (G_F)	[4,7]
Michel parameters	[4,7]
T, P violation	[4,7]
μ catalyzed fusion	[8]
CPT test	[4]
muon capture: $\mu^- p \rightarrow n \nu$	[4,7,9]
muon number violating decays: $\mu^+ \rightarrow e^+ \gamma$	[4,6,7,10-12]
$\mu^+ \rightarrow e^+ e^+ e^-$	[4,6,7]
$\mu^- N \rightarrow e^- N$	[4,6,7,13]
$\mu^+ e^- \rightarrow \mu^- e^+$	[4,7]
muonic atoms (QED tests, nuclear charge distributions)	[4,7,14]
condensed matter (μSR)	[4]

The standard model rates for the four muon-number violating processes in the table are all extremely small. Thus significant results from any of these experiments could provide important constraints on physics beyond the standard model, for example the existence of supersymmetry processes. All recent experiments of this type have been done or are proposed using surface muon beams [4]. These beams originate from the decays of pions that have stopped in the production target. High-intensity stopping pion and other muon beamlines could be provided from the NF target.

An approved experiment at PSI will improve the sensitivity on $\mu \rightarrow e \gamma$ using a surface muon beam with an intensity of $5\ 10^8$ μ/s. Using a higher muon rate than this runs into difficulties with accidental $e \gamma$ coincidences. The last experiment that examined the mode $\mu \rightarrow e e e$ used a rate of $6\ 10^6$ μ^+/s. Increasing the event rate leads to problems with the tracking detectors required to measure the three charged particles in the final state. A slow beam spill is desirable for these experiments. Muonium is the atomic bound state $\mu^+ e^-$. Muonium-antimuonium conversion involves the transition $\mu^+ e^- \rightarrow \mu^- e^+$. The experiment searches for the two final state leptons in coincidence. A pulsed beam is preferred to take advantage of characteristic timing signals from the conversion process.

Coherent $\mu \to e$ conversion in matter is a promising approach to studying new muon number violating processes. The proposed MECO experiment [7,13,15-7] looks for a single final state electron with energy near 105 MeV. Since there is only one particle in the final state, higher beam rates aren’t limited by accidental coincidences. A pulsed beam is preferred to reduce beam-related backgrounds. However, there may be difficulties for the MECO experiment from the time structure of the NF phase 1 proton driver beam. MECO requires a muon bunch approximately every microsecond and searches for the conversion electron in a 400 ns time window between bunches. The NF beam comes in a train of 6 short bunches separated by 20 ms. The next train comes about 300 ms later. A new proton accumulator ring would probably be necessary to match the time structure if this option were seriously pursued.

There are also a number of non-muon physics topics that could make use of the high intensity beam available from the driver. Some of the most compelling of these experiments, listed in Table 4, involve studies of rare decays of the kaon.

Table 4 Kaon decay topics using the proton driver

$K_L \to \mu e$ (BR)	[6,18]
$K^+ \to \pi^+ \mu e$ (BR)	[6,19]
$K_L \to \pi^o \mu e$ (BR)	[6]
$K^+ \to \pi^+ \nu \nu$ (BR)	[6,20-1]
$K_L \to \pi^o \nu \nu$ (BR)	[6,20-1]
$K^+ \to \pi^o \mu^+ \nu$ (transverse polarization)	[6,19,20]
$K^+ \to \mu^+ \nu \gamma$ (transverse polarization)	[6]
$K^+ \to \pi^+ \mu \mu$ (spin-spin polarization)	[6,20]
$K_L \to \mu \mu$ (correlation effects)	[6,18]
$K^o \to \pi \pi \pi$ (CP violation)	[20]
$K^o \to \pi \pi \gamma$ (CP violation)	[20]
$K_S \to \pi^o e e$ (BR)	[20]

The $K \to \pi \nu \nu$ decay modes have a number of nice theoretical features and give important information about the V_{td} element in the CKM matrix and about CP violation. Pursuing this type of physics would require the construction of a high-quality kaon beam line off the target area.

There are, in addition, many intermediate-energy [22] and other hadron physics [20,23] topics that could be addressed with this facility. One could also use the phase 1 beam as a source for intense beams of low energy neutrinos [2].

3. Phase 2 Opportunities

Upon the completion of phase 2 of the NF project, there will be available a high-intensity cooled muon beam with the properties listed in Table 5.

Table 5 Muon beam parameters

<p>	203	MeV/c
σ_p	21	MeV/c
σ_x	15	mm
$\sigma_{x'}$	94	mr
bunch spacing	5	ns
σt	0.51	ns
N_{bunch}	6 x 67	
$N\mu$ / bunch	$4.2\ 10^{10}$	
f_{rep}	2.5	Hz
Polarization	0.16	

This muon beam has a total intensity of $4\ 10^{13}$ μ/s. The time structure is very complex. There is an overall 400 ms cycle time. Inside this there are 6 bursts of muons separated from each other by 20 ms. Each burst is further subdivided into 67 individual muon bunches separated from each other by 5 ns. The muon beam should be extremely pure. Very few of the pions or kaons produced at the target will survive the 550 m path to the end of the cooling section. In addition there is 17.2 m of liquid hydrogen in the mini-cooling and dispersed through the main cooling sections. This should range out any hadrons left in the beam.

Although the muon intensity is very high, there are a number of attributes of this beam that makes it unsuitable for many of the muon experiments discussed in the previous section. The beam momentum of 200 MeV/c is relatively high for experiments that require muons stopped in a thin target. The rms momentum spread of 10% is also high, while the polarization of 16% is low. In addition, the beam has a bunched time structure, which is unsuitable for coincidence experiments. Two experiments that might be improved using this beam are searches muon to electron conversion in matter (MECO) and for the electric dipole moment (EDM) of the muon.

3.1 MECO

The currently approved experiment at BNL [7,13,15-7] expects to have an available beam flux of 10^{11} μ^-/s. The phase 2 NF beam has an intensity 500 times larger than this. However, much of this intensity gain would be lost because the experiment requires the muons to be stopped in a thin aluminum target. There may also be significant background problems from the electrons resulting from the decays in flight of muons that do not stop in the target. The stopping efficiency and background problems could be improved by decelerating the muon beam. It might be possible to do this by running the NF cooling system linac at an rf phase that does not fully compensate for the energy loss in the hydrogen absorbers, but this could degrade the properties of the muon beam.

There are also difficulties for the MECO experiment from the time structure of the phase 2 NF beam. MECO requires a muon bunch approximately every microsecond and searches for the conversion electron in a 400 ns time window between bunches. The NF bunches comes every 5 ns over a period of ~340 ns and then stop for 20 ms. A 200 MeV/c accumulator ring would probably be required to fix the time structure if this option were seriously pursued.

3.2 EDM experiment

The discovery of a muon electric dipole moment would indicate a new source of CP violation and point to physics beyond the standard model. A three-phase program [24-5] of EDM studies is under consideration at BNL. The first two phases would use the existing g-2 ring and expects to use a beam flux of 7 10^7 μ/s [6,7]. The goal of phase 3 is a sensitivity of 10^{-24} e-cm. This requires the number of muon decays times polarization squared of $NP^2 = 10^{16}$. This is not possible in a reasonable amount of running time without neutrino factory technology. Therefore, phase 3 of the EDM experiment would require a new ring at the site of the NF front-end.

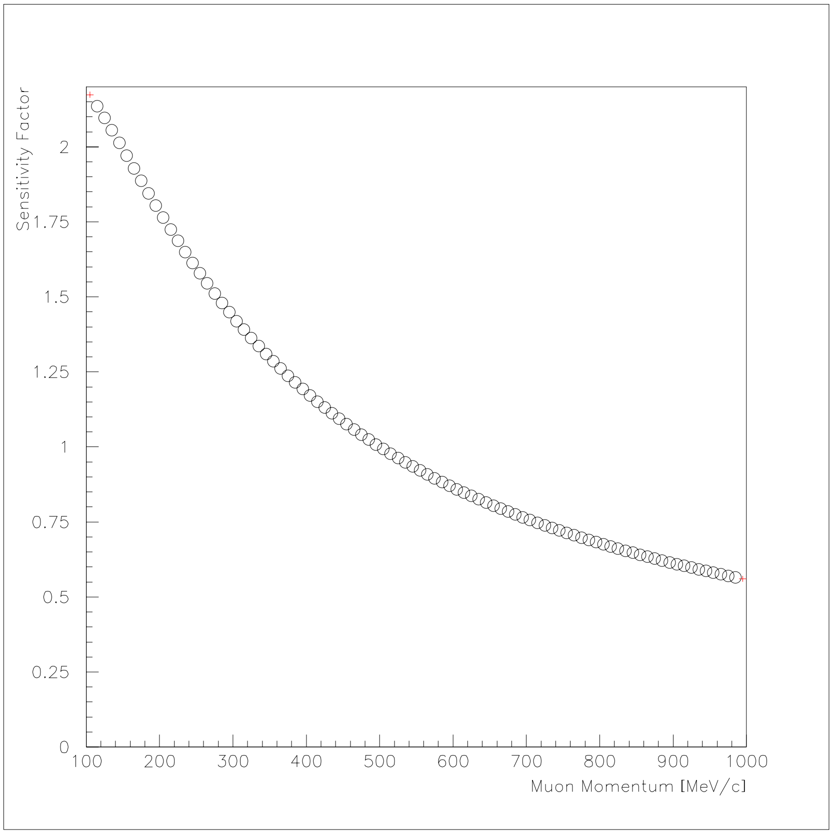

Figure 1. Sensitivity factor for the EDM experiment as a function of momentum [courtesy Y. Semertzidis].

The design of the new ring would be guided by the extensive experience obtained during the earlier running at the g-2 ring. The first question is the optimal muon storage momentum. The sensitivity factor vs. muon momentum is shown in Fig. 1, assuming an average radial E field of 2 MV/m and that the measurement begins 4 μs after injection.

The sensitivity factor is given by

$$SF = \gamma\, \beta \times B \sqrt{\{\exp(-4\ \mu s / \gamma\tau)\}}$$

The sensitivity vanishes at the magic momentum of 3.1 GeV/c. The g-2 ring (R=7.1 m) is a reasonable place to begin, since the sensitivity factor is within a factor of two of the maximum. Lower muon momentum results in better sensitivity, until $p < m_\mu c$, after which β falls rapidly. However, the energy of the decay positrons is smaller for lower energy rings and this is unfavorable from the detector point of view, since it is more difficult to see the signal over the backgrounds from neutrons, etc. The choice of the operating momentum and design of an optimized phase 3 ring will depend on the experience gained running at the present g-2 ring and detailed Monte Carlo simulations.

If there are strong reasons for using a momentum higher than 200 MeV/c, the beginning sections of the linac could be included in this phase of the NF project in order to accelerate the muons to the required momentum. The NF time structure seems fine for this experiment since the muons would be injected into the ring over the 340 ns bunch train length and then 20 ms would be available for the measurement before the next train of muons arrived.

The NF produces a muon beam with a potential NP^2 factor per second

$$NP^2 = 4.2\ 10^{13} \times (0.16)^2 = 1\ 10^{12}$$

This could, in principle, produce the required sensitivity level for the experiment in 10^4 seconds. In practice mismatches between the muon beam emittance and the likely ring acceptance will degrade the effective NP^2 factor. The momentum spread of the beam (10%) is large compared to typical ring designs (1%). If the length of the bunch train (100 m) is larger than the circumference of the ring, there may be additional injection losses. Unless the ring has a large aperture, there will also be losses from the transverse size and divergence of the beam. Until a ring is designed it is not possible to make a firm estimate of these losses, but a factor of a few times 10^{-3} seems like a reasonable first guess. This would imply that the required sensitivity could be reached in less than a year of running.

4. Phase 3 Opportunities

One possible use of a high-energy muon beam is for an improved g-2 experiment [7]. The higher intensity available from the NF should significantly reduce the statistical errors. However, this experiment requires muons with the "magic" momentum of 3.1 GeV/c. This is higher than the 2.5 GeV/c available from the NF linac, so this experiment would require in addition the completion of at least one of the RLA linacs as well. At the moment repeating this experiment with greater accuracy is not compelling since theoretical uncertainties from hadronic vacuum polarization effects dominate the comparison of theory with experiment.

5. Conclusions

We have seen that there is a significant physics program that could sensibly be matched to a staged construction of an AGS-based NF. In the first phase MECO and/or one of the rare kaon decay searches could make use of the intense hadron fluxes produced at the NF target. In the second phase an EDM search can make effective use of the cooled medium-energy muon beam. Of all the very interesting physics options considered, this experiment would mesh most easily with the proposed NF infrastructure and beam characteristics. In the third phase a new g-2 experiment could be performed, if reductions in the theoretical uncertainty make a new more-sensitive experiment desirable.

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